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External financing, channel power structure and product green R&D decisions in supply chains

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Abstract

Purpose – This study aims to focus on the optimal green R&D of a capital-constrained supply chain under different channel power structures as well as the impact of capital constraint, financing cost, channel power structure and cost-reducing efficiency on green R&D and supply chain profitability.

Design/methodology/approach – A two-echelon supply chain is considered. The upstream firm engages in green R&D but has capital constraints that can be overcome by external financing. Green R&D is beneficial to reduce production costs and increase consumer demand. Based on whether or not the upstream firm is capital constrained and dominates the supply chain, four models are developed.

Findings – Capital constraints significantly lower green R&D and supply chain profitability. Transferring leadership from the upstream to the downstream firms leads to higher green R&D levels and downstream firm profitability, whereas the upstream firm's profitability is increased (decreased) if green R&D investment efficiency is high (low) enough. Greater financing costs reduce green R&D and downstream firm profitability; however, the upstream firm's profitability under the model in which it functions as the follower increases if the initial capital is sufficient. More importantly, empirical analysis based on practice data is used to verify the theoretical results reported above.

Practical implications – This study reveals how upstream firms in supply chains decide green R&D decisions in situations with capital constraints, providing managers and governments with an understanding of the impact of capital constraint, channel power structure, financing cost and cost-reducing efficiency on supply chain green R&D and profitability.

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Originality/value – The major contributions are the exploration of supply chain green R&D by taking into consideration channel power structures and cost-reducing efficiency and the validation of theoretical results using practice data.

Keywords Capital constraint, External financing, Channel power structure, Green supply chain

Paper type Research paper

1. Introduction

Product green R&D is a critical strategic issue that has sparked growing concern among supply chain firms. In general, supply chain firms can participate in product green R&D in a variety of ways, including raising the environmentally friendless level of the product (Ghosh and Shah, 2012), improving resources utilization efficiency (Song and Gao, 2018; Das *et al.*, 2022), optimizing manufacturing processes (Ge *et al.*, 2014; Sana, 2022a) and lowing carbon emissions (Chen and Akmalul'Ulya, 2019), among others. For example, Adidas developed environmentally friendly technologies such as MMVEA and Eco-Grip to lessen the environmental impact of their manufacturing items (Ghosh and Shah, 2012). Other well-known worldwide firms, such as Canon, Acer, Dell and Xerox, have also invested in green R&D to increase green operation efficiency and reduce carbon emissions (Chen and Akmalul'Ulya, 2019). However, it should be noted that apart from the external forces derived from laws and regulations, the demand expansion effect and the cost reduction effect are two primary incentives that drive firms to invest in product green R&D activities (Ranjan and Jha, 2019; Hong *et al.*, 2023). Some practice surveys have found that green R&D plays an important influence in stimulating customer demand, such as Accenture's report, which demonstrated that more than 80% of customers will evaluate the green characteristics of items in their purchasing process (Hong and Guo, 2019). Concerning the cost reduction effect of green R&D, Pepsi Cola's green R&D investment in the use of reusable plastic shipping containers saves 196 million dollars (Ranjan and Jha, 2019). Additionally, Xerox's green operations have effectively reduced energy consumption by 31%, assisting in the reduction of operating and production costs (Chen and Akmalul'Ulya, 2019). Without a doubt, an increase in consumer demand and a decrease in operating (production) costs both contribute to increased revenue or profit, motivating supply chain firms to concentrate more on green R&D.

However, it can be observed that there are also a large number of firms that put in less effort to engage in product green R&D (Ghosh and Shah, 2015). The primary reason is that investing in product green R&D is not free and instead incurs a substantial cost for firms (Yang and Chen, 2018). Especially, when these firms face capital constraints, undertaking the effort for green R&D of the product is a significant barrier for them even while it is a tremendous potential to gain market share and enhance operational performance. Therefore, seeking financing to ease firms' capital pressures may be an effective strategy to incentivize them to enhance the green R&D of the product. For the present period, external financing, such as bank credit financing and bond financing, is a major and prevalent channel that supply chain firms have prioritized for investments in product green R&D activities. For example, the China Green Finance Development Research Report 2021 revealed that China's green credit balance in 2021 exceeded 15.9 trillion yuan. In 2022, Baosteel Group Corporation issued 500 million yuan of low-carbon transformation green corporate bonds to support its construction of a hydrogen-based vertical furnace system project. It is simple to comprehend that the capital constraints and the related financing cost will have a substantial impact on the green R&D decisions of firms facing capital constraints, changing the contractual connection among supply chain firms and their corresponding performance.

The primary goal of this research is to investigate how capital constraints impact supply chain firms' investing incentives in green R&D and corresponding performance, as well as whether supply chain firms make different green R&D decisions when the channel power structure changes. More specifically, based on the situation that product green R&D can stimulate increased consumer demand and lower production costs, this study mainly focuses on the following questions. (1) What are the optimal green R&D decisions, optimal price decisions, optimal consumer demand and corresponding optimal performance of supply chain firms under different channel power structures when the upstream firm is capital constrained or not? (2) Under what condition is the upstream firm motivated to seek financing from external channels? And how do capital constraints, financing costs and cost reduction effects of green R&D affect the upstream firm's green R&D decision and supply chain firm performance? (3) How do channel power structures influence the upstream firm's green R&D decisions? (4) Can the above-mentioned relevant results be supported by practice data?

To address the aforementioned concerns, this study considers a two-echelon supply chain with an upstream firm and a downstream firm linked by a wholesale price contract. The upstream firm faces capital constraints and invests in improving the product's green R&D level, which increases consumer demand while decreasing production costs. The upstream firm chooses green R&D and wholesale price, whereas the downstream firm decides on market price (or retail margin). This study constructs four supply chain game models by considering whether the upstream firm dominates the supply chain or not and whether capital is constrained or not. With the equilibriums, this study first characterizes the upper and lower limits of the upstream firm's initial capital under different models, revealing the conditions under which the upstream firm needs to seek financing when facing capital constraints. Following that, this study compares the levels of green R&D and profitability in four models to investigate the effects of capital constraints and channel power structures. Then, the comparative static analysis is used to examine the impacts of financing cost and cost reduction efficiency on the manufacturer's green R&D decision and supply chain performance. Finally, this study presents the empirical analysis based on a sample of Chinese listed firms obtained from the China Stock Market Accounting Research (CSMAR) database to validate the relevant conclusions about the effects of capital constraints, channel power structures and financing costs on equilibrium solutions.

This study mainly contributes to three aspects listed below.

First, driven by the benefits of product green R&D on raising consumer demand and lowering production cost, this study designs supply chain models by taking capital constraints into account under different channel power structures. A lot of studies have discussed the green R&D investment strategies in the supply chain under capital constraints, however, few have considered the cost reduction effect of green R&D and capital constraints in combination.

Second, this study examines the impact of financing costs and channel power structures on supply chain green R&D decisions and performance. The results reveal that a greater financing cost results in lower product green R&D level and downstream firm profitability, whereas the upstream firm's profit will increase if the initial capital is high enough in the downstream firm-led Stackelberg model. Additionally, in the downstream firm-led Stackelberg model, both the product green R&D level and the downstream firm's profitability are higher than in the upstream firm-led Stackelberg model, while the comparison of the upstream firm's profitability depends on the green R&D investment efficiency.

Finally, and most importantly, the influences of finance costs and channel power structures are studied using practice data, and the majority of the aforementioned theoretical results are confirmed by practice.

The remainder of this study is organized as follows. In Section 2, we summarized the literature related to our research setting and contributions. Section 3 describes the conceptual framework and development of the model. Section 4 characterizes the optimal decisions for different supply chain structures and whether or not capital is constrained. Section 5 delves into comparative statics. In Section 6, we employ practice data to validate the results presented in Section 5. The managerial insights and conclusion of our work are highlighted in Section 7 and Section 8, respectively. All proofs of the propositions are given in Appendix.

2. Literature review

This study focuses on the capital-constrained upstream firm's green R&D decisions in the supply chain under different channel power structures, as well as how financing costs, channel power structures and cost-reducing efficiency, among other things, affect the supply chain's interplay and corresponding profits. This study is closely related to four streams of literature: (1) green R&D decisions, (2) cost reduction efficiency of the product (green) R&D, (3) channel power structure and (4) capital constraint. Accordingly, a summary of the relevant literature is listed below. In addition, Table 1 also provides a summary of the relevant literature.

2.1 Supply chain (quality) R&D decisions

This study contributes to the stream of literature on the supply chain green (quality) R&D decisions. For example, Xu *et al.* (2017) studied the green R&D and production decisions in the supply chain with a manufacturer and a retailer under the assumption that the green technology of the manufacturer is conducive to reducing carbon emissions. Yang and Chen (2018) considered the revenue-sharing and cost-sharing contracts provided by the retailer to motivate the manufacturer to invest in green R&D for reducing carbon emissions. Song and Gao (2018) explored the manufacturer's optimal green R&D decisions in the supply chain under two types of revenue-sharing contracts, i.e. the revenue-sharing contract negotiated by the manufacturer and the retailer or determined solely by the retailer. Assuming that the demand function depends on the green R&D level, service effort level and market price, Ranjan and Jha (2019) investigated the manufacturer's optimal green R&D decision and the retailer's service effort decision in a dual-channel supply chain. Heydari *et al.* (2021) examined

Paper	Green R&D	Green R&D sensitive demand	Cost reduction	Channel power structure	Upstream firm capital constraint	External financing
Mondal and Giri (2022)	√	√	×	×	×	×
Sana (2022b)	√	√	×	×	×	×
Chen *et al.* (2023)	√	√	×	√	×	×
Hong *et al.* (2023)	√	√	√	×	×	×
Wu *et al.* (2019)	√	√	×	×	×	√
Yang *et al.* (2019)	√	√	×	×	×	√
Peng *et al.* (2023)	√	√	×	×	√	√
Tang and Yang (2020)	√	√	×	√	×	√
This paper	√	√	√	√	√	√

Source(s): Created by authors

Table 1. Summary of previous literature

green R&D and pricing decisions in the supply chain faced with a linear consumer demand relying on green R&D and market price. Ma *et al.* (2021) investigated the effect of government regulation on the manufacturer's decision on green technology R&D for reducing carbon emissions. Mondal and Giri (2022) examined the manufacturer's and retailer's green R&D decisions, as well as their performance, in two types of revenue-sharing contracts that are determined entirely by the retailer and bargained by both the manufacturer and the retailer, respectively. Sana (2022b) investigated the optimal green R&D decisions of the supply chain by considering two types of demand functions. Even though the above studies have considered the optimal green R&D decisions under the assumption of green R&D sensitive demand, they all fail to consider the cost reduction effect of green R&D as well as the impact of capital constraints on green R&D decisions under different channel power structures.

2.2 Impact of (green) R& D on cost reduction

The second stream of literature relevant to this study has examined the effects of (green) R&D on lowering production costs. For example, assuming upstream and downstream firms' R&D in lowering production cost, Ge *et al.* (2014) proved that R&D collaboration can only create a win-win scenario in the supply chain if the contribution levels are Pareto matched. By considering a supply chain with isoelastic demand, Hu *et al.* (2019) constructed four distinct models in which each firm can solely or cooperatively, or independently invest in R&D to lower production costs and identified the conditions under which a firm's investment in R&D leads to a higher level of R&D and supply chain performance. Fu *et al.* (2021) considered a platform supply chain with a supplier, an online platform firm and a third-party logistics firm (3PL) and investigated the 3PL's optimal equity financing for the investment in technology R&D to reduce the transportation cost. However, the studies mentioned above all fail to take into account the assumption that consumer demand is dependent on (green) R&D. Moreover, these studies do not consider the case of the supply chain firms facing capital constraint and thus neglect to examine the optimal (green) R&D choices and to compare the differences between the models with and without capital constraints. These studies have also ignored the impact of channel power structures on (green) R&D decisions.

By assuming that process R&D can increase consumer demand and decrease production costs, Genc and De Giovanni (2020) investigated the optimal pricing and R&D investment decisions in a closed-loop supply chain. With a similar consumer demand assumption, Hong *et al.* (2023) optimized the green R&D and quality decisions made by the upstream firm concurrently or by two supply chain members separately and revealed that the upstream firm making both green R&D and quality decisions contributes to higher levels of green R&D and quality as well as supply chain performance than the separate decision case. Differing from the above two studies, this study focuses on the green R&D decisions in the supply chain with capital constraints and different channel power structures.

2.3 Impact of channel power structure on green R&D decisions

Another relevant focus of research in the literature is the influence of channel power structures on green R&D initiatives in the supply chain. Ghosh and Shah (2012), for example, examined green R&D strategies in the clothing serial supply chain in the context of environmentally conscious customers and identified which channel power structure model contributes to greater green R&D level and supply chain performance. Chen *et al.* (2019) investigated the optimal green R&D decisions of two supply chain participants in cooperation and non-cooperation scenarios while taking the channel power relationship into account. Guan *et al.* (2020) examined the manufacturer's green R&D decisions and the retailer's advertising effort decision in supply chain models under different channel power structures while considering Nash bargaining fairness concerns and found that compared to fairness-neutral scenarios, the fairness-concerned will change the comparative relationship of the levels of green R&D and advertising effort under different channel power structures. Fan *et al.* (2020) investigated the impact of cost-sharing on the manufacturer's green R&D decisions in the manufacturer-led and retailer-led Stackelberg models, finding that as cost-sharing increases, the manufacturer does not change its green R&D decision in the manufacturer-led Stackelberg model but increases the green R&D level in the retailer-led Stackelberg model. Chen *et al.* (2023) investigated the effect of channel power structures on green energy R&D strategies in the electricity supply chain with an electricity generator and an electricity retailer and reported that the Nash game model has the greatest degree of green R&D. This research differs from the aforementioned studies in three ways. First, in addition to characterizing the influence of green R&D on consumer demand, this study examines the efficacy of green R&D in lowering production costs. Second, this study models the supply chain game with and without capital constraints and compares the differences between them. Third, this study investigates the influence of financing cost, cost-reducing efficiency and channel power structures on green R&D decisions and supply chain performance.

2.4 Impact of capital constraints on green R&D decisions

Finally, this study devotes to the work on the investigation of the influence of capital constraints on green R&D decisions. For example, Wu *et al.* (2019) examined the manufacturer's carbon emission investment decisions under the assumption that the retailer is capital-constrained and can seek financing through bank financing and trade credit financing. Yang *et al.* (2019) studied the manufacturer's optimal green R&D decisions in a supply chain with one manufacturer and two capital-constrained retailers, where retailers can conduct operations using external financing or trade credit. Cao *et al.* (2019) investigated the financial preferences of the supply chain when a downstream manufacturer invests in carbon abatement but lacks funds and can seek financing from an upstream supplier or an external channel. Tang and Yang (2020) investigated the impact of financing mechanisms (bank loans and early payment) and power structures on the operational decisions of a low-carbon supply chain that consisted of a capital-constrained manufacturer and a capital-abundant retailer. Peng *et al.* (2023) investigated the manufacturer's optimal carbon emission reduction decisions in an e-commerce supply chain under the bank credit and cost-sharing financing schemes. In a closed-loop supply chain comprising a supplier and a capital-constrained OEM, Zhang and Chen (2022) have compared the effects of three different financing strategies on the supplier's remanufacturing decisions. Differing from the aforementioned studies, this study assumes that green R&D is beneficial in lowering operating or manufacturing costs. More importantly, this study uses practice data to validate theoretical findings.

3. Model description

Considering a two-tiered decentralized supply chain comprised of an upstream and a downstream firm. The supply chain members are linked by a wholesale price contract, through which product transactions are conducted between them. The upstream firm manufactures products and invests in product green R&D activities, such as improving product greenness, optimizing product manufacturing processes and increasing resource utilization efficiency, among others. Assume that the upstream firm is facing the capital constraint that makes it impossible to continue with normal production tasks and product green R&D investment. As a result, the upstream firm has the incentive to seek external financing to ensure that its decisions on product green R&D investment and production (or wholesale price) are optimal for profit maximization. Moreover, in terms of the supply chain focusing on product green R&D under the condition of capital constraint, we have the following necessary assumptions and settings for the model construction and equilibrium analysis.

First, we assume that the upstream firm manufactures $q(q > 0)$ units of products at a unit production cost $c(c > 0)$ and then sells them to the downstream firm at a wholesale price w, where $w > c$. After purchasing, the downstream firm then serves the consumers in the final market at a sales price p, where $p > w$. Without loss of generality, we do not consider product inventory in our supply chain model, which means that the upstream firm's production quantity equals the downstream firm's ordering quantity and also equals the final consumer demand.

Second, we assume that the upstream firm usually invests in product green R&D and the level of the product green R&D is assumed to be $\theta(\theta > 0)$. Accordingly, to achieve the product green R&D level of θ, the upstream firm needs to perform the green R&D investment at a cost of $\frac{1}{2}k\theta^2$, where k measures the efficiency of green R&D investment. Clearly, a higher k generally indicates a lower investment efficiency in product green R&D, implying that the upstream firm should invest more to improve one unit of product green R&D level. This type of green R&D investment cost function has been very commonly used in the literature on supply chain management, such as in studies by Fan *et al.* (2020), Chen *et al.* (2023) and Hong *et al.* (2023).

Suppose that one of the primary objectives of product green R&D investment is to reduce production costs. Ge *et al.* (2014), for example, clearly show that R&D on process improvement can lower production costs. In practice, Apple invests in green R&D to use clean energy, which can significantly reduce energy consumption and thus operating costs. As a result of the investment in product green R&D, the upstream firm's unit production cost is reduced from c to $c(1-\delta\theta)$. Here, δ denotes the cost-reducing efficiency, which is the same as that of Ge *et al.* (2014) and Hong *et al.* (2023). One can see that a higher δ indicates that the product green R&D investment is more effective in reducing the production cost. Furthermore, as shown by Ge *et al.* (2014) and Hong *et al.* (2023) that the cost reduction would not exceed the original unit production cost, the range of cost-reducing efficiency we assume is $\delta \in \left(0, \frac{1}{\theta}\right)$.

Moreover, we set that the upstream firm has an initial capital $S(>0)$ to organize its product production and green R&D investment. If the upstream firm's initial capital is no less than its capital expenditure, which is the sum of product production costs and green R&D investment cost, i.e. $S \geq c(1-\delta\theta)q + \frac{1}{2}k\theta^2$, the upstream firm faces no capital constraint and can continue to operate normally while determining the wholesale price and product green R&D at an optimal level to maximize profit. However, if $S < c(1-\delta\theta)q + \frac{1}{2}k\theta^2$, the upstream firm faces a capital constraint of $L = c(1-\delta\theta)q + \frac{1}{2}k\theta^2 - S$ and has no choice but to seek capital support for operations. Assume that the upstream firm has the option of obtaining external financing, such as bank loaning. Obviously, the amount of money borrowed by the upstream firm to ensure its normal product production and green R&D investment is L. However, the upstream firm must also pay the interest cost for the financing from the external channel, and we assume that the financing interest (or financing cost) is $r(0 \leq r \leq 1)$.

Furthermore, we assume that except for the cost-reducing effect, product green R&D also exerts a positive impact on consumer demand. In other words, if the upstream firm improves its product green R&D, consumers are willing to pay a higher price for products or consume more at a given sales price. Thus, based on the studies of Xu *et al.* (2017) and Hong *et al.* (2023), we assume that the consumer's inverse demand function is

$$p = a - \beta q + \lambda\theta, \tag{1}$$

where a is the initial market potential, β denotes the price sensitivity to demand and a higher β means the consumer will change its demand less in response to a change in the sales price of the product, λ measures the impact of the product green R&D level on the sales price and a higher λ indicates a higher price that the consumers are willing to pay for per unit of green R&D improvement.

Based on the assumptions stated above, we formulate the profit functions of the upstream and the downstream firms under capital constraints as follows:

$$\pi_u = [w - c(1 - \delta\theta)]q - \frac{1}{2}k\theta^2 - rL, \tag{2}$$

$$\pi_d = (p - w)q. \tag{3}$$

In this study, we investigate two different channel power structures: the upstream and the downstream firms act as the leader of the supply chain, respectively. Thus, in the upstream firm-led model, the decision sequences of both firms in the supply chain are as follows. First, the upstream firm chooses its optimal product green R&D and wholesale price decisions to maximize profit; second, by learning the upstream firm's decision information and applying the profit maximization principle, the downstream firm determines the optimal sales price decision. In the downstream firm-led model, the downstream firm decides the sales price first, followed by a response from the upstream firm, which determines product green R&D and wholesale price.

Next, we will discuss the equilibrium results under the two different channel power structure models in the following section. However, to satisfy the non-negative optimal solution and the negative definite Hessian matrix, as well as to ensure that the optimal results are in the same range for the comparative analysis, the following two conditions should be met: $\lambda > c\delta$ and $k > \frac{(c\delta+\lambda)[\lambda(a+c)+2\lambda]}{4\beta}$. Furthermore, the condition $\lambda > c\delta$ obviously means that the green R&D of the product has a greater impact on the sales price rather than the cost, implying that improving the green R&D level of the product increases the willingness of consumers to pay a higher price for the green product or persuades more consumers to purchase the green product more effectively than lowering the production cost. The condition $k > \frac{(c\delta+\lambda)[\lambda(a+c)+2\lambda]}{4\beta}$ shows that the efficiency of green R&D investment is insufficient, implying that it is difficult for the upstream firm to improve the product's green R&D level. Similar assumptions can be seen in studies by Fan *et al.* (2017, 2023), Chen *et al.* (2023) and Hong *et al.* (2023).

4. Equilibrium results

4.1 Upstream firm-led model with no capital constraint

We begin by exploring the equilibrium decisions and corresponding profits in the upstream firm-led model with no capital constraint (denoted as the UN model), which serves as a benchmark model to that with capital constraint. Thus, with Equa. (2) and Equa. (3), the upstream firm's and the downstream firm's profit functions can be expressed as follows:

$$\pi_u = [w - c(1 - \delta\theta)]q - \frac{1}{2}k\theta^2, \tag{4}$$

$$\pi_d = (p - w)q. \tag{5}$$

This is a two-stage Stackelberg game model that can be solved by backward induction. First, substituting Equa.(1) into Equa.(5), one can see that $\frac{\partial^2 \pi_d}{\partial p^2} = -\frac{2}{\beta} < 0$, indicating that the downstream firm's profit π_d is strictly concave in p. Hence, by taking the derivative of π_d with respective to p, we have:

$$p = \frac{1}{2}(a + w + \lambda\theta). \tag{6}$$

Then, substituting Equa.(6) into Equa.(4), we can find that Hessian matrix $H = \begin{bmatrix} -k + \frac{c\delta\lambda}{\beta} & \frac{\lambda - c\delta}{2\beta} \\ \frac{\lambda - c\delta}{2\beta} & -\frac{1}{\beta} \end{bmatrix}$ is negative definite, which indicates that π_u is strictly concave in w and θ. So, by taking the derivatives of π_u with respective to w and θ, respectively, we can obtain the optimal wholesale price and product green R&D:

$$w^{*un} = \frac{2k\beta(a + c) - c(c\delta + \lambda)(a\delta + \lambda)}{4k\beta - (c\delta + \lambda)^2}, \tag{7}$$

$$\theta^{*un} = \frac{(a - c)(c\delta + \lambda)}{4k\beta - (c\delta + \lambda)^2}, \tag{8}$$

where the superscript "$*un$" represents the UN model, in which the upstream firm leads the supply chain and faces no capital constraint. Now, substituting Equa. (7) and Equa. (8) into Equa. (6), the optimal sales price is derived as follows:

$$p^{*un} = \frac{k\beta(3a + c) - c(c\delta + \lambda)(a\delta + \lambda)}{4k\beta - (c\delta + \lambda)^2}. \tag{9}$$

This, together with Equa.(7) and Equa.(8), indicates that the optimal consumer demand and the two supply chain members' optimal profits are as follows:

$$q^{*un} = \frac{k(a - c)}{4k\beta - (c\delta + \lambda)^2}, \tag{10}$$

$$\pi_d^{*un} = \frac{k^2\beta(a - c)^2}{\left[4k\beta - (c\delta + \lambda)^2\right]^2}, \tag{11}$$

$$\pi_u^{*un} = \frac{k(a - c)^2}{2\left[4k\beta - (c\delta + \lambda)^2\right]}. \tag{12}$$

Therefore, we derive the following proposition.

P1. In the UN model, the optimal product green R&D level, the optimal wholesale price, the optimal sales price, the optimal consumer demand, and the optimal profits of two members of the supply chain are given by Equa.(7)–Equa.(12), respectively. Moreover, the lower limit of the initial capital of the upstream firm should satisfy

$$S \geq S^{*un} = c(1 - \delta\theta^{*un})q^{*un} + \frac{1}{2}k\left(\theta^{*un}\right)^2 = \frac{k(a - c)\left[c\left(8k\beta - c(a + c)\delta^2\right) - 4c^2\delta\lambda + \lambda^2(a - 3c)\right]}{2\left[4k\beta - (c\delta + \lambda)^2\right]^2}.$$

4.2 Downstream firm-led model with no capital constraint

This section considers another benchmark model in which the upstream firm is not constrained by capital but the downstream firm acts as the leader (denoted as the DN model). We can solve it using backward induction. Following Fan *et al.* (2020), we first define $m = p - w$, which denotes the downstream firm's retail margin. Thus, given the wholesale price decision, the downstream firm's sales price decision is equivalent to the retail margin decision. Then, substituting Equa.(1) and $m = p - w$ into Equa.(4), the upstream firm's profit function can be rewritten as follows:

$$\pi_u = [w - c(1 - \delta\theta)]\frac{a - (w + m) + \lambda\theta}{\beta} - \frac{1}{2}k\theta^2. \tag{13}$$

The upstream firm determines the optimal product green R&D and wholesale price to maximize its profit. We can demonstrate that the upstream firm's profit π_u is strictly concave in w and θ because Hessian matrix $H = \begin{bmatrix} -k + \dfrac{2c\delta\lambda}{\beta} & \dfrac{\lambda - c\delta}{\beta} \\ \dfrac{\lambda - c\delta}{\beta} & -\dfrac{2}{\beta} \end{bmatrix}$ is negative definite. Thus, according to $\frac{\partial \pi_u}{\partial \theta} = 0$ and $\frac{\partial \pi_u}{\partial w} = 0$, we have:

$$\theta = \frac{(a - c - m)(c\delta + \lambda)}{2k\beta - (c\delta + \lambda)^2}, \tag{14}$$

$$w = \frac{k\beta(a + c - m) - c(c\delta + \lambda)(a\delta - \lambda + m\delta)}{2k\beta - (c\delta + \lambda)^2}. \tag{15}$$

Then, substituting Equa.(14) and Equa.(15) into Equa.(5), we can see that the downstream firm's profit π_d is strictly concave in m because of $\frac{\partial^2 \pi_d}{\partial m^2} = -\frac{1}{\beta} < 0$. Thus, according to $\frac{\partial \pi_d}{\partial m} = 0$, the downstream firm's optimal retail margin can be derived as follows:

$$m^{*dn} = \frac{a - c}{2}. \tag{16}$$

where the superscript "$*dn$" represents the DN model in which the upstream firm faces no capital constraint while the downstream firm acts as the leader.

Then by substituting Equa.(16) into Equa.(14) and Equa.(15), we can derive the following:

$$\theta^{*dn} = \frac{(a - c)(c\delta + \lambda)}{4k\beta - 2(c\delta + \lambda)^2}, \tag{17}$$

$$w^{*dn} = \frac{k\beta(a + 3c) - c(c\delta + \lambda)(a\delta + c\delta + 2\lambda)}{4k\beta - 2(c\delta + \lambda)^2}. \tag{18}$$

Thus, from Equa.(16)–Equa.(18), we can obtain the optimal sales price, the optimal consumer demand, and the two supply chain members' optimal profits as follows:

$$p^{*dn} = \frac{k\beta(3a + c) - (c\delta + \lambda)[c\lambda + a(2c\delta + \lambda)]}{4k\beta - 2(c\delta + \lambda)^2}, \tag{19}$$

$$q^{*dn} = \frac{k(a - c)}{4k\beta - 2(c\delta + \lambda)^2}, \tag{20}$$

$$\pi_d^{*dn} = \frac{k(a-c)^2}{8k\beta - 4(c\delta+\lambda)^2}, \tag{21}$$

$$\pi_u^{*dn} = \frac{k(a-c)^2}{8\left[2k\beta - (c\delta+\lambda)^2\right]}, \tag{22}$$

Thus, Proposition 2 can be derived as follows.

P2. In the DN model, the optimal product green R&D level, the optimal wholesale price, the optimal sales price, the optimal consumer demand and the optimal profits of two members of the supply chain are given by Equa.(17)–Equa.(22), respectively. Moreover, the lower limit of the upstream firm's initial capital should meet

$$\begin{aligned} S \geq S^{*dn} &= c\left(1-\delta\theta^{*dn}\right)q^{*dn} + \frac{1}{2}k\left(\theta^{*dn}\right)^2 \\ &= \frac{k(a-c)\left[c\left(8k\beta - c(a+3c)\delta^2\right) - 8c^2\delta\lambda + \lambda^2(a-5c)\right]}{8\left[2k-(c\delta+\lambda)^2\right]^2}. \end{aligned}$$

4.3 Upstream firm-led model with capital constraint

This section investigates the optimal solution and corresponding profits of the two supply chain members in the model that the upstream firm acts as the supply chain leader and seeks financing through an external channel when facing capital constraints (denoted as the UE model). With Equa. (2) and Equa. (3), we can solve this Stackelberg model by adopting the solution approach used in the UN model. Thus, the following proposition is derived in which the superscript "*ue" represents the UE model.

P3. In the UE model, the optimal product green R&D level, the optimal wholesale price, the optimal sales price, the optimal consumer demand and the optimal profits of two supply chain members are given as follows:

$$\theta^{*ue} = \frac{[a-c(1+r)][c\delta(1+r)+\lambda]}{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2}, w^{*ue} = \frac{(1+r)\{2k[a+c(1+r)] - c[c\delta(1+)+\lambda](a\delta+\lambda)\}}{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2},$$

$$q^{*ue} = \frac{k(1+r)[a-c(1+r)]}{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2}, p^{*ue} = \frac{(1+r)[k\beta[3a+c(1+r)] - c[c\delta(1+r)+\lambda](a\delta+\lambda)\}}{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2},$$

$$\pi_d^{*ue} = \frac{k^2\beta(1+r)^2[a-c(1+r)]^2}{\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^2}, \pi_u^{*ue} = \frac{k(1+r)[a-c(1+r)]^2}{2\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}} + rS.$$

Moreover, the upper limit of the upstream firm's initial capital is

$$S < S^{*ue} = c\left(1-\delta\theta^{*ue}\right)q^{*ue} + \frac{1}{2}k\left(\theta^{*ue}\right)^2$$

$$= \frac{k[a-c(1+r)]^2\left\{8kc\beta(1+r) + [c\delta(1+r)+\lambda]\left\{\begin{array}{c}\lambda[a-c(1+r)] \\ -c(1+r)(a\delta+\lambda) \\ -c(1+r)[c\delta(1+r)+\lambda]\end{array}\right\}\right\}}{2\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^2}.$$

We can directly observe from Proposition 3 that the upstream firm's profit is influenced by its initial capital and the higher the initial capital, the higher the profit. Indeed, a higher initial capital means that the upstream firm will borrow less money from the external channel. As a result, the upstream firm should not pay excessive interest costs for financing, which is beneficial to the upstream firm's profitability. However, an interesting observation is that the upstream firm's product green R&D and wholesale price decisions are unaffected by the initial capital. The reason for this is that regardless of the scale of the upstream firm's initial capital, its capital requirement for product green R&D investment and production can be guaranteed through financing. Thus, when making decisions on product green R&D and wholesale price, the upstream firm will disregard its initial capital. This also means that the downstream firm's decision and profit will not be affected by the initial capital. However, all decisions made by the two supply chain members and their profits will be influenced by the financing cost.

4.4 Downstream firm-led model with capital constraint

In this section, we look at the downstream firm-led model with capital constraint (DE model) and derive the corresponding optimal results according to backward induction. We denote this model with the superscript "*de" and obtain the following proposition by solving this Stackelberg model from Equa. (2) and Equa. (3).

P4. In the DE model, the optimal product green R&D level, the optimal wholesale price, the optimal sales price, the optimal consumer demand and the optimal profits of the two supply chain members are given as follows:

$$\theta^{*de} = \frac{[a - c(1+r)][c\delta(1+r) + \lambda]}{2\left\{2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right\}},$$

$$w^{*de} = \frac{(1+r)[k\beta[a + 3c(1+r)] - c[c\delta(1+r) + \lambda][\delta[a + c(1+r)] + 2\lambda]\}}{2\left\{2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right\}},$$

$$p^{*de} = \frac{c(1+r)\{k\beta(1+r) - \lambda[c(1+r)\delta + \lambda]\} + a\{3k\beta(1+r) - [c\delta(1+r) + \lambda]\}[2c\delta(1+r) + \lambda\}}{2\left\{2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right\}},$$

$$q^{*de} = \frac{k(1+r)[a - c(1+r)]}{2\left\{2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right\}}, \pi_d^{*de} = \frac{k(1+r)[a - c(1+r)]^2}{4\left\{2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right\}},$$

$$\pi_u^{*de} = \frac{k(1+r)[a - c(1+r)]^2}{8\left\{2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right\}} + rS.$$

Moreover, the upper limit of the upstream firm's initial capital is

$$S < S^{*de} = c\left(1 - \delta\theta^{*de}\right)q^{*de} + \frac{1}{2}k\left(\theta^{*de}\right)^2$$

$$= \frac{k[a - c(1+r)]\left[3c^3\delta^2(1+r)^3 - a\lambda^2 + c^2\delta(1+r)^2(a\delta + 8\lambda) - c(1+r)\left[8k\beta(1+r) - 5\lambda^2\right]\right\}}{8\left[2k\beta(1+r) - [c\delta(1+r) + \lambda]^2\right]^2}.$$

Similar to Proposition 3, Proposition 4 demonstrates in the DE model that, except for the upstream firm's profit, the initial capital has no effect on the supply chain operating decisions and the corresponding downstream firm's profit, whereas the financing cost influences all decisions and profits of the supply chain.

5. Analysis

5.1 Effects of upstream firm's initial capitals

Exploring the effects of initial capital can help us better understand the terms on which the upstream firm needs to seek financing from an external channel. Thus, we will provide a comparison between the upper and lower limits of the initial capital under the previous four Stackelberg models.

> *P5.* Under the UN and UE models, it holds that $S^{*un} > S^{*ue}$; under the DN and DE models, it holds that $S^{*dn} > S^{*de}$; under the UN and DN models, it holds that $S^{*un} < S^{*dn}$; under the UE and DE models, it holds that $S^{*ue} < S^{*de}$.

Proposition 5 first demonstrates that, regardless of whether the upstream or the downstream firm acts as the leader of the supply chain, the lower limits of initial capital in models without capital constraints are always greater than the upper limits of the initial capital in models with capital constraints, i.e. $S^{*un} > S^{*ue}$ and $S^{*dn} > S^{*de}$. Seeing Figure 1 for a distinct comparison. This result is extremely straightforward. When there is no capital constraint, the upstream firm can use its capital arbitrarily and at no cost, allowing it to pursue higher levels of product green R&D and production volume. Accordingly, greater initial capital is needed. However, an initial capital below the lower limit does not automatically imply that the upstream firm will choose the financing. One can see clearly from Figure 1 that only when $S < S^{*ue}$ in the upstream firm-led model and $S < S^{*de}$ in the downstream firm-led model, respectively, does the upstream firm demand financing for product green R&D investment and production. Otherwise, when $S^{*ue} \le S < S^{*un}$ and $S^{*de} \le S < S^{*dn}$, the upstream firm will continue its product green R&D investment and production under capital constraint conditions.

Furthermore, Proposition 5 illustrates that, no matter whether or not the upstream firm encounters capital constraints, the upper (lower) limit of initial capital is lower in the

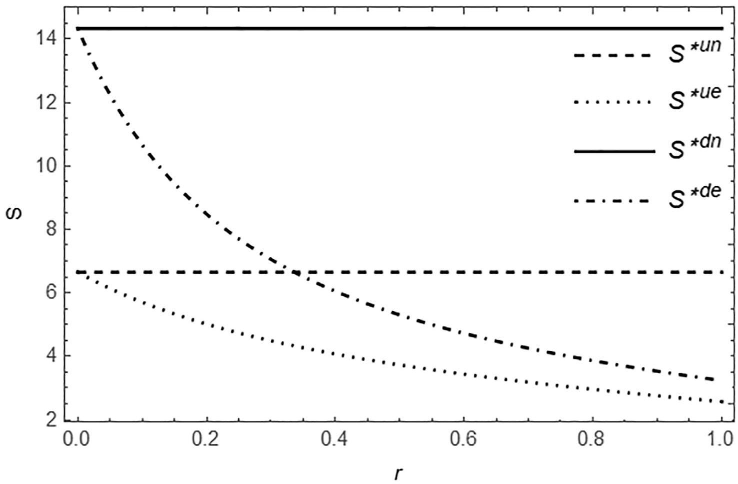

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Figure 1.
Impact of the financing cost on the upper and lower limits of the initial capital ($a = 8$, $c = 2$, $\beta = 1$, $\lambda = 4$, $k = 15$, $s = 2$ and $\delta = 0.1$)

upstream firm-led model than in the downstream firm-led model, i.e. $S^{*un} < S^{*dn}$ and $S^{*ue} < S^{*de}$. This implies that, when acting as a leader in the supply chain, the upstream firm's willingness to invest in product green R&D and production is lower than when acting as a follower. This contradicts some existing publications, such as Guan *et al.* (2020) and Agi and Yan (2020), which state that an upstream dominant firm is generally more likely to increase product green R&D and produce more products.

5.2 Effects of capital constraints

This subsection seeks to examine how capital constraints affect product green R&D decisions and the profits of the two supply chain members. In this regard, we compare the corresponding optimum results obtained in models with and without capital constraints under different channel power structures. This analysis will assist us in recognizing whether financing under capital constraint conditions can facilitate the supply chain to achieve the outcomes of the non-capital constraint scenario.

P6. Under the UN and UE models, it holds that $\theta^{*un} > \theta^{*ue}$, $\pi_d^{*un} > \pi_d^{*ue}$ and $\pi_u^{*un} > \pi_u^{*ue}$; under the DN and DE models, it holds that $\theta^{*dn} > \theta^{*de}$, $\pi_d^{*dn} > \pi_d^{*de}$ and $\pi_u^{*dn} > \pi_u^{*de}$.

Proposition 6 reveals that, in the context of the upstream firm acting as the supply chain's leader, in comparison to the scenario with no capital constraint (the UN model), the upstream firm's incentive to improve product green R&D level is relatively lower when facing capital constraint (the UE model), resulting in lower profitability for both supply chain members. This finding implies that, even if the upstream firm can relieve its capital pressure through external financing, it is still unable to determine the level of product green R&D equivalent to that in the scenario without capital constraint. The immediate cause is that the upstream firm must pay the interest cost for financing, which impedes its optimal product green R&D decision. Consequently, lower product green R&D will result in lower profits for supply chain members by lowering consumer demand. Furthermore, Proposition 6 also shows that when the downstream firm dominates the supply chain, the comparative results between models with and without capital constraints are the same as that when the upstream firm is the leader. The above comparison results are also supported by the numerical analysis in Figures 2–5. The managerial revelations underlying Proposition 6 are summarized as follows. To begin with, any firm should pay close attention to its case flow, which allows it to make optimal decisions. Second, there is no such thing as a free lunch for the firm, even if it can resolve the capital constraint problem through financing. In addition, financing remains inadequate to address inefficiencies caused by capital constraints on supply chain members.

5.3 Effects of channel power structures

The purpose of this subsection is to investigate the impact of channel power structures on product green R&D decisions and corresponding profits of the two supply chain members. To be more specific, we first compare the two benchmark models to demonstrate the importance of channel power structures in influencing the upstream firm's product green R&D decisions and the supply chain's profitability. Following that, we make the comparison in the presence of capital constraints to see whether the aforementioned comparison results are changed by capital constraints.

P7. Under the UN and DN models, it holds that $\theta^{*un} < \theta^{*dn}$ and $\pi_d^{*un} < \pi_d^{*dn}$, whereas $\pi_u^{*un} > (<)\pi_u^{*dn}$ if $k > (<)\frac{3(c\delta+\lambda)^2}{4\beta}$; under the UE and DE models, it holds that $\theta^{*ue} < \theta^{*de}$ and $\pi_d^{*ue} < \pi_d^{*de}$, whereas $\pi_u^{*ue} > (<)\pi_u^{*de}$ if $k > (<)\frac{3[c\delta(1+r)+\lambda]^2}{4\beta(1+r)}$.

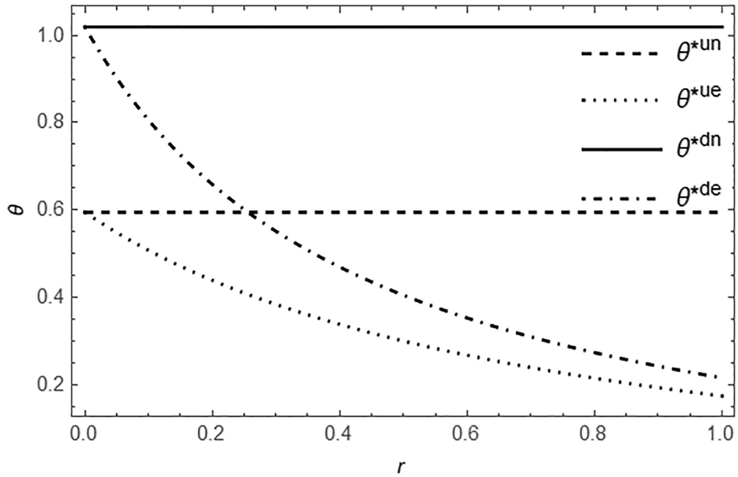

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Figure 2.
Impact of the financing cost on green R&D ($a = 8, c = 2, \beta = 1, \lambda = 4, k = 15, S = 2$ and $\delta = 0.1$)

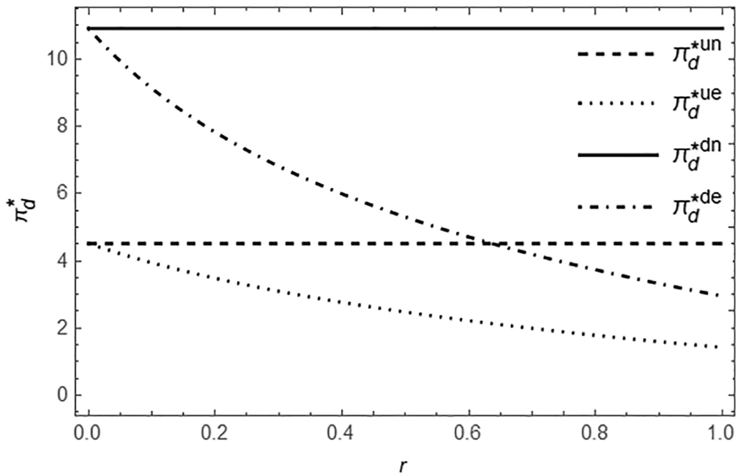

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Figure 3.
Impact of the financing cost on the downstream firm's profit ($a = 8, c = 2, \beta = 1, \lambda = 4, k = 15, S = 2$ and $\delta = 0.1$)

According to Proposition 7, a direct finding is that capital constraints do not affect the comparative results for product green R&D level and the downstream firm's profit under different channel power structures. That is, regardless of whether the upstream firm suffers from capital constraints, the results of the above comparison between the upstream and downstream firm-led models are indifferent. However, the capital constraint has a significant impact on the comparisons of the upstream firm's profits under different channel power structures.

More specifically, a counterintuitive comparison result on product green R&D can be seen first. According to most existing studies, an upstream firm acting as a leader in the supply chain usually has a stronger incentive to improve product green R&D investment because it

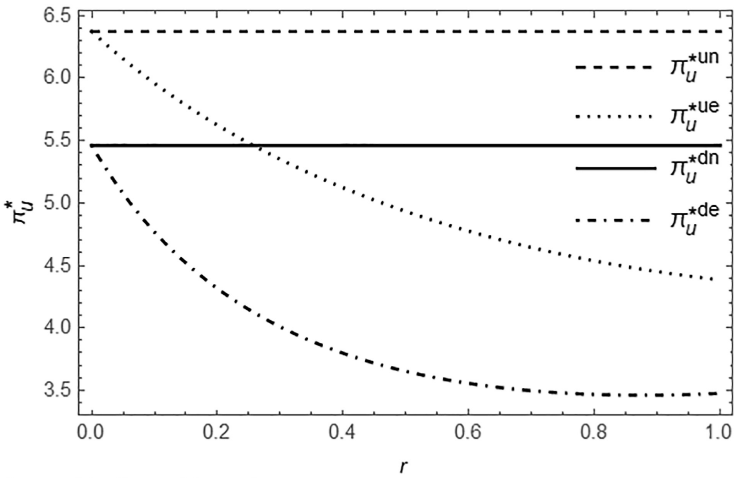

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Figure 4.
Impact of the financing cost on the upstream firm's profit ($a = 8$, $c = 2, \beta = 1, \lambda = 4$, $k = 15, S = 2$ and $\delta = 0.1$)

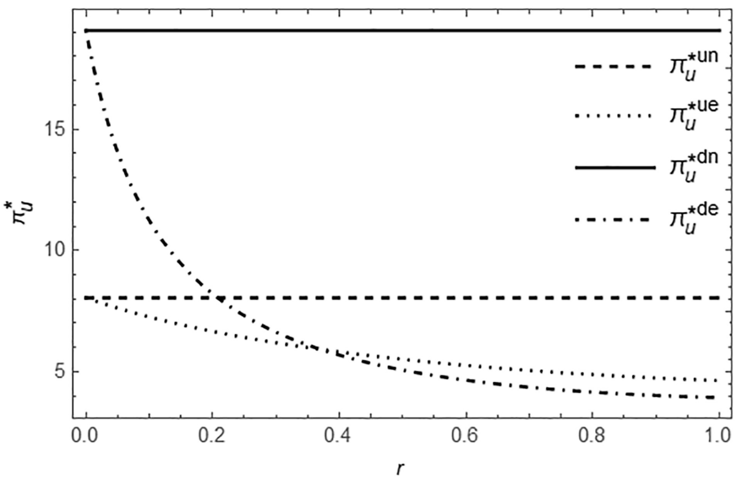

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Figure 5.
Impact of the financing cost on the upstream firm's profit ($a = 8$, $c = 2, \beta = 1, \lambda = 4$, $k = 10, S = 2$ and $\delta = 0.1$)

can capture more profit relative to the downstream follower (Guan *et al.*, 2020; Agi and Yan, 2020). However, our finding shows that the level of product green R&D is relatively higher when the upstream firm acts as a follower rather than a leader. One can also see Figure 2 for a visual comparison. The intuitive reason for this result is that, as the supply chain leader, the downstream firm will exert more pressure on the upstream firm for improving product green R&D level due to the effectiveness of product green R&D in increasing consumer demand and lowering the wholesale price as production cost decreases.

Naturally, higher product green R&D leads to higher profit for the downstream firm by increasing consumer demand. This is consistent with the observation in the existing literature that a higher channel power is generally indicative of a higher profit (Ghosh and

Shah, 2015; Chen *et al.*, 2023; Fan *et al.*, 2020). The numerical result in Figure 3 also demonstrated it. However, this is not the case for the upstream firm. Moreover, a higher product green R&D level does not always imply a higher benefit for the upstream firm. One can see from Proposition 7 that whether the upstream firm's leadership results in higher profit is determined by the efficiency of green R&D investment. Specifically, if the efficiency of the investment in improving green R&D is low (high), the profit of the upstream firm is higher (lower) when it acts as a leader in the supply chain rather than as a follower. The reason behind this is that the profit of the upstream firm is determined by two effects: the green R&D investment cost effect, which reduces profit, and the consumer demand effect, which raises profit. Clearly, when the green R&D investment efficiency is low, the cost effect of investment in green R&D outweighs the effect of consumer demand. Consequently, when acting as a leader, the upstream firm's weaker incentive to improve product green R&D will induce it to invest less in product green R&D, which in turn will benefit its profit. Otherwise, increased consumer demand induced by higher product green R&D will result in higher profit when the upstream firm acts as a follower. Additionally, it should be pointed out that because of the financing cost, the threshold value of the efficiency of green R&D investment in the scenario with the capital constraint differs from the scenario without the capital constraint. As depicted in Figures 4 and 5, if the efficiency of green R&D investment is high enough ($k = 15$), the upstream firm's profit is higher when acting as a leader than when acting as a follower, whereas the comparison of the upstream firm's profits in scenarios with capital constraints under different channel power structures is determined by the financing cost if the efficiency of green R&D investment is low enough ($k = 10$).

5.4 Effects of financing costs

The primary aim of this subsection is to examine the effects of financing costs (interest costs) on product green R&D decisions and profits of two supply chain members under different channel power structures when the upstream firm faces capital constraints. This investigation can assist managers in recognizing the importance of financing costs in the firm's green R&D investment and guide them to choose an appropriate external financing channel by taking into account the effect of financing costs and the firm's status among supply chain members.

P8. With the increase in the financing cost r, under the UE model, it holds that $\frac{\partial\theta^{*\mathrm{ue}}}{\partial r} < 0, \frac{\partial\pi_d^{*ue}}{\partial r} < 0$ and $\frac{\partial\pi_u^{*ue}}{\partial r} < 0$; under the DE model, it holds that $\frac{\partial\theta^{*\mathrm{de}}}{\partial r} < 0$ and $\frac{\partial\pi_d^{*de}}{\partial r} < 0$, whereas $\frac{\partial\pi_u^{*de}}{\partial r} > (\leq)0$ if $S > (\leq)S^{\#}$.

Proposition 8 demonstrates that in the UE model, where the upstream firm faces capital constraints and serves as the supply chain leader, the upstream firm's incentive to improve product green R&D decreases with the financing cost, resulting in lower profits for two supply chain members. Higher financing cost indicates that a greater proportion of the upstream firm's revenue procured from product green R&D improvement ought to be paid to the substance that provides the external financing, which naturally diminishes the upstream firm's incentive to further improve product green R&D level. Also, this reduces the profits of both supply chain members. Without a doubt, in the scenario where the downstream firm acts as the leader (DE model), higher financing costs will also reduce the upstream firm's product green R&D level as well as the downstream firm's profit. The above results are also shown in Figures 2–5.

However, in contrast to the UE model, the impact of the financing cost on the upstream firm's profit in the DE model is dependent on the initial capital. It demonstrates that if the upstream firm's initial capital is insufficient, implying that more financing is required, its profit decreases with the financing cost, which is the same as in the UE model. Surprisingly, if the upstream firm has sufficient initial capital, its profit will increase with the financing cost, indicating that the upstream firm can benefit from a higher financing cost at a specific condition. As displayed in Figure 2, as the financing cost increases, its effect on the product green R&D level is significantly larger in the DE model than in the UE model, prompting a faster decline in the product green R&D level as well as consumer demand. Hence, the upstream firm's total costs, including product production and green R&D investment costs, will diminish faster than the increment in the financing cost, contributing to an increase in profit. By observing Figures 4 and 6, the numerical results also show that the upstream firm's profit in the DE model decreases in the financing cost if $S = 1.5$ but decreases first and then increases if $S = 2$.

5.5 Effects of production cost-reducing efficiency

In this subsection, we investigate the impact of the production cost-reducing efficiency on product green R&D decisions and supply chain profits and check whether the product cost-reducing efficiency can cause differential effects under different channel power structures.

P9. With the increase in the production cost-reducing efficiency δ, under the UE model, it holds that $\frac{\partial \theta^{*ue}}{\partial \delta} > 0, \frac{\partial \pi_d^{*ue}}{\partial \delta} > 0$ and $\frac{\partial \pi_u^{*ue}}{\partial \delta} > 0$; under the DE model, it holds that $\frac{\partial \theta^{*de}}{\partial \delta} > 0, \frac{\partial \pi_d^{*de}}{\partial \delta} > 0$ and $\frac{\partial \pi_u^{*de}}{\partial \delta} > 0$.

Proposition 9 demonstrates that regardless of channel power structures, an increase in production cost-reducing efficiency leads to an increase in product R&D, bringing about higher profits for the two supply chain members. Undoubtedly, higher efficiency in reducing production costs driven by product green R&D will urge the upstream firm to invest more in product green R&D improvement, resulting in a higher product green R&D level. Increased product green R&D level benefits both supply chain members by increasing consumer demand. Moreover, decreased production costs permit the upstream firm to lower the wholesale price, which likewise helps to increase the profits of the two supply chain members

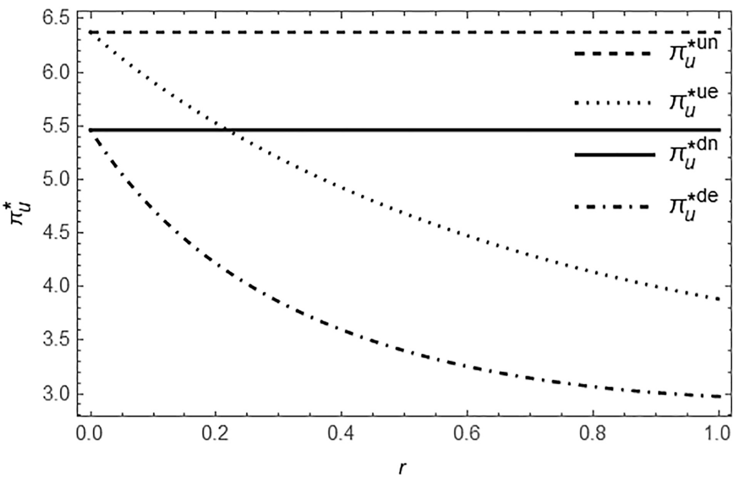

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Figure 6. Impact of the financing cost on the upstream firm's profit ($a = 8$, $c = 2$, $\beta = 1$, $\lambda = 4$, $k = 15$, $S = 1.5$ and $\delta = 0.1$)

because a lower product market price determined by the downstream firm increases consumer demand. In this manner, the profits of the two supply chain members are increasing with the production cost-reducing efficiency. This proposition reveals that product green R&D that enhances production efficiency can benefit each member of the supply chain. Additionally, the results in Proposition 9 are also supported by the numerical analysis in Figure 7.

6. Empirical tests

6.1 Data and sample

The theoretical conclusions in Section 5 are summarized here from the perspective of the upstream firm, which serves as the main investor of green R&D. (1) Capital constraints reduce green R&D and upstream firm profitability. (2) The downstream firm's leadership benefits green R&D, but if the green R&D investment efficiency is low (high), the upstream firm's profitability increases (decreases). (3) Financing costs reduce green R&D and upstream firm profitability, with the exception of the downstream firm serving as the leader case, where the upstream firm's profitability is raised if its initial capital is sufficient.

This section will examine these predictions using a sample of Chinese A-share listed firms during 2007 and 2019. The sample begins in 2007 because new accounting standards for firms listed in China were implemented in that year. The initial sample is cleaned as follows: first, financial firms are excluded; second, ST and *ST firms are excluded; third, samples are excluded with data errors in which return on assets (ROA) is less than -1; and last, all financial variables are winsorized at the 1% and 99% levels to restrict the impact of outliers. The final sample consists of 5,105 firm-year observations from 1,635 firms. Green innovation and financial data are sourced from the CSMAR database.

6.2 Variable definition

The green R&D level is measured by the number of green patent applications (Li *et al.*, 2022). Upstream firm profitability is quantified by Return on Assets (ROA) and Return on Equity (ROE). Capital constraints are measured by the WW index (Whited and Wu, 2006). The firm

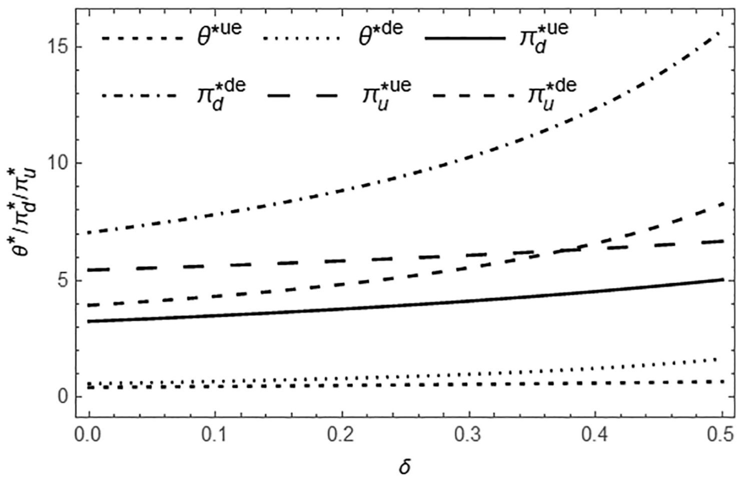

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Figure 7.
Impact of the cost-reducing efficiency on R&D and supply chain profits ($a = 8$, $c = 2$, $\beta = 1$, $\lambda = 4$, $k = 15$, $S = 2$ and $r = 0.2$)

with a higher WW index has greater capital constraints. The channel power structure is measured by customer concentration, which is determined by the ratio of a supplier's largest customer's sales to the supplier's overall sales (Dhaliwal *et al.*, 2016; Wang and Mao, 2021). A smaller value of the ratio indicates a lower level of customer concentration, implying that the upstream firm has more power to influence the supply chain. Financing cost is estimated by the debt cost, calculated as the interest expense divided by total liabilities (Pittman and Fortin, 2004).

The detailed definitions are shown in Table 2. The firms are ranked each year by WW index, customer concentration and debt cost, respectively, and 30th and 70th percentiles are computed as data breakpoints. Using the 30th and 70th percentiles of WW index, customer concentration and debt cost, the firms are divided into three groups, respectively.

Table 3 reports the summary statistics for the variables. The mean of number of green patent applications is about 8, which is more than the median of 3 and is much less than the maximum of 139. On average, the ratio of supplier's largest customer's sales to supplier's overall sales is 13.554%. The average ROA and ROE are 0.045 and 0.074, respectively. The mean of WW Index is −1.026. In addition, the average proportion of interest expense to total liabilities is 0.017.

6.3 Impact of capital constraints on green R&D and upstream firm profitability

Figure 8 examines the impact of capital constraints on the green R&D level. It shows that when the WW index rises, so do green patent applications, implying that a firm with more capital constraints will reduce its green R&D investment. This empirical result is consistent with the corresponding theoretical result in Proposition 6.

Variable	Definition
Green R&D	Number of green patent applications
ROA	Return on assets
ROE	Return on equity
WW index	$WW = -0.091CF - 0.062DIV + 0.021TLTD - 0.044SIZE + 0.102ISG - 0.035SG$ Where CF is the ratio of cash flow to total assets, DIV is an indicator that takes the value of 1 if the firm pays cash dividends, $TLTD$ is the ratio of the long-term debt to total assets, SIZE is the natural log of total assets, ISG and SG are the sales growth of industry and firm, respectively
Channel power structure	Ratio of supplier's largest customer's sales to supplier's overall sales (%)
Debt financing cost	Ratio of interest expense to total liabilities

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Table 2. Definitions of variables

Variable	Mean	SD	Min	p25	p50	p75	Max
Green R&D	8.403	18.138	1	1	3	7	139
ROA	0.045	0.050	−0.154	0.019	0.044	0.071	0.183
ROE	0.074	0.094	−0.415	0.039	0.076	0.118	0.300
Channel power structure	13.554	12.512	0.900	5.280	9.350	17.350	64.520
WW index	−1.026	0.068	−1.223	−1.066	−1.021	−0.981	−0.877
Debt financing cost	0.017	0.012	0.000	0.007	0.016	0.025	0.046

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Table 3. Descriptive statistics for the variables

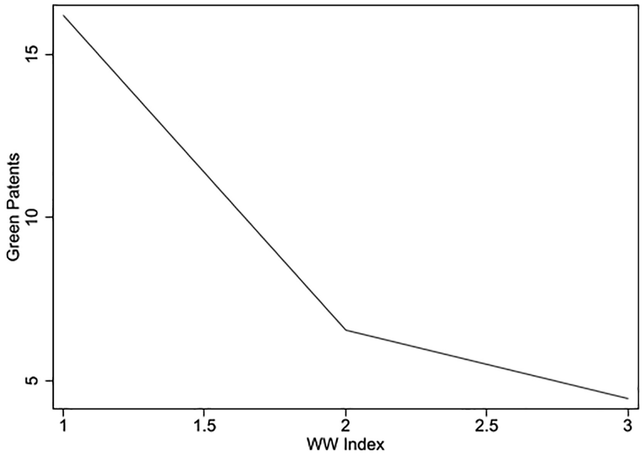

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Figure 8.
Impact of capital constraints on green R&D

Figure 9 examines the impact of capital constraints on upstream firm profitability. It reveals that both ROA and ROE fall as WW index rises, indicating that increased capital constraints result in lower upstream firm profitability. Proposition 6's corresponding theoretical result is consistent with this empirical evidence.

6.4 Impact of channel power structure on green R&D and upstream firm profitability

Figure 10 examines how the channel power structure influences the green R&D level. As seen in Figure 10, as the upstream firm's channel power declines, the number of green patent applications increases, implying that the upstream firm's motivation to improve green R&D

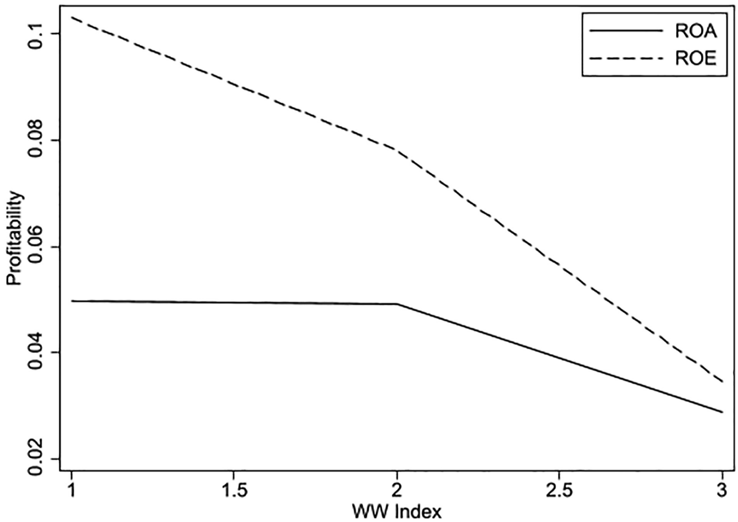

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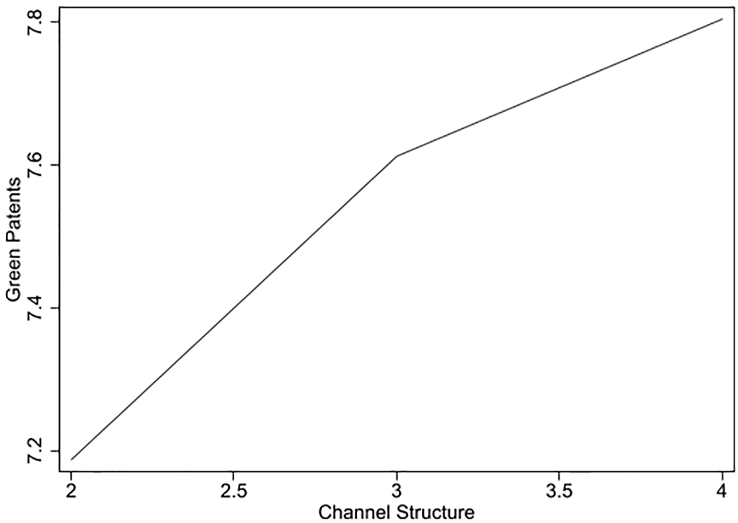
Figure 9.
Impact of capital constraints on upstream firm profitability



Source(s): Created by authors

Figure 10. Impact of channel power structure on green R&D

increases. Naturally, this empirical evidence fully supports the theoretical result in Proposition 7.

Figure 11 investigates the influence of channel power structure on the profitability of the upstream firm. The empirical study shows that as channel power declines, both ROA and ROE fall, meaning that the upstream firm's profitability decreases as well. When the upstream firm's green R&D investment efficiency is low enough, this empirical result is completely consistent with the corresponding theoretical result in Proposition 7, but it

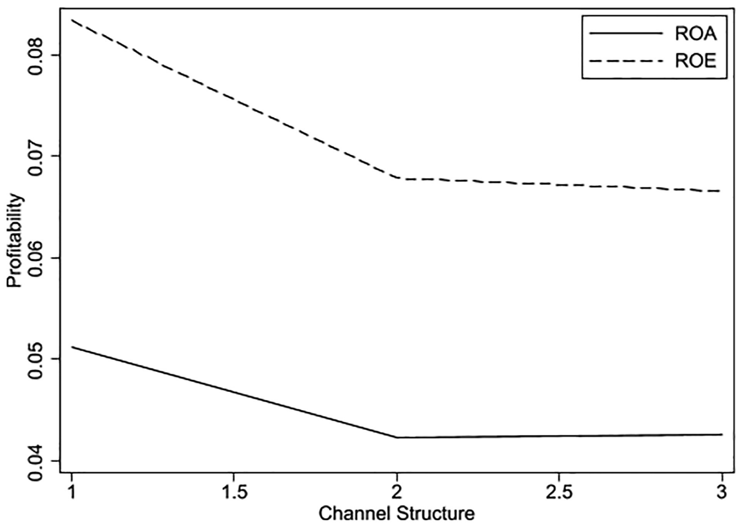


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Figure 11. Impact of capital constraints on upstream firm's profitability

contradicts the theoretical result when the green R&D investment efficiency is high enough. But in practice, firms' green R&D investment efficiency is typically low since they must invest more in green R&D improvement while getting less green R&D output.

6.5 Impact of financing costs on green R&D and upstream firm profitability

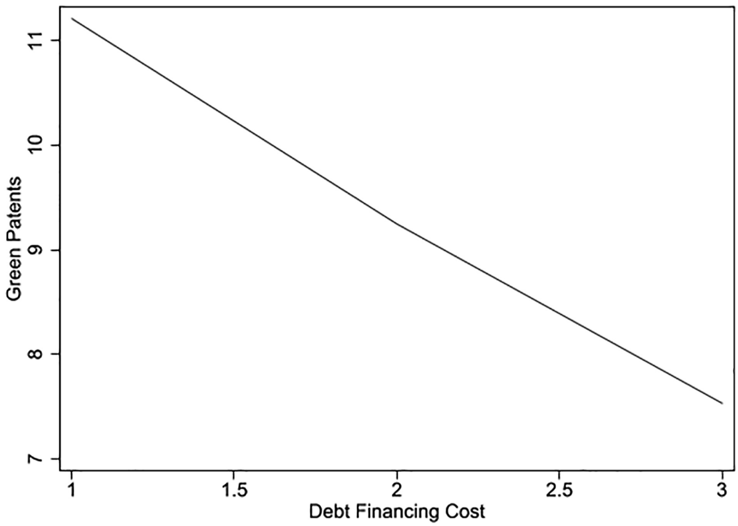
Figure 12 depicts the empirical result of the influence of financing costs on the level of green R&D. The result suggests that green patent applications will decrease as financing costs increase. This indicates that rising financing costs lower the motivation for the upstream firm to improve its green R&D level. This empirical evidence supports the theoretical findings in Proposition 8.

Figure 13 explores the effect of financing costs on the upstream firm's profitability. It highlights that when financing costs rise, both ROA and ROE fall, showing that rising financing costs impair the upstream firm's profitability. This empirical result is completely congruent with the corresponding theoretical result in Proposition 8 under the UE model. Additionally, if the initial capital is low enough, the theoretical result under the DE model is also corroborated by the empirical result. Even though the upstream firm's profitability is increased if its initial capital is sufficient under the DE model, it should be noted that in practice, firms typically face severe capital constraints and are compelled to pay high interest expenditure for financing, especially as the financing cost rises. The profitability of firms with capital constraints is lowered logically.

7. Managerial implications

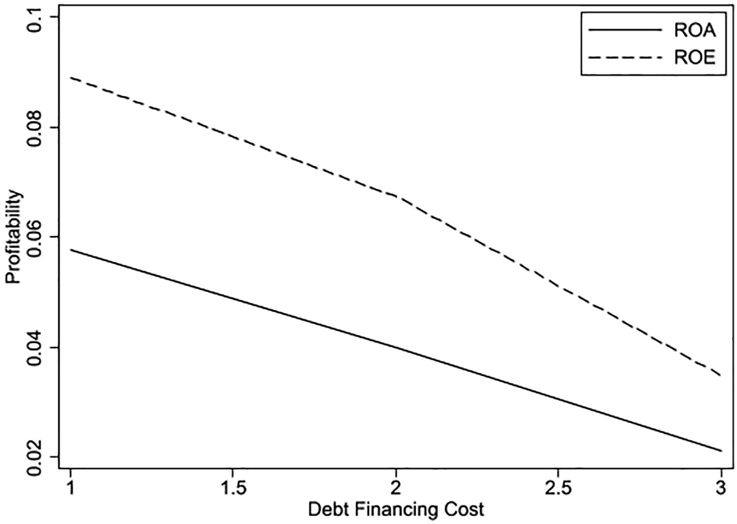
Based on the previous analysis of equilibrium results under models with and without capital constraints, we can derive the following managerial implications.

(1) Even though supply chain firms suffer capital constraints in their green R&D and product manufacturing operations, it does not guarantee that they will seek financing right now. Our findings indicate that supply chain firms seek external financing only



Source(s): Created by authors

Figure 12. Impact of debt financing cost on green R&D



Source(s): Created by authors

Figure 13.
Impact of debt financing cost on upstream firm's profitability

when their initial capital is low enough. Furthermore, even if capital constraints may be addressed through financing, the level of green R&D and supply chain operational performance cannot be achieved to the same extent as in the absence of capital constraints. These findings explain why so many firms in practice, particularly middle and small-sized firms, are reluctant to invest in green product R&D. These findings can help firms in the supply chain choose when to seek external finance if they lack the initial capital to invest in green R&D and produce green products. In addition, it is advised that government regulatory agencies formulate new green financing policies to reduce financing pressure and cost, therefore, enhancing supply chain firms' incentives to engage in the improvement of green R&D.

(2) The channel power structures have a significant impact on supply chain firms' decisions on product green R&D, and hence on their profitability. Therefore, firms should consider their status in the supply chain when seeking financing and determining their investment in green R&D. Increased cost-reducing efficiency pushes supply chain firms to improve product green R&D and profitability. This implies that supply chain firms should actively seek green R&D activities that improve operation efficiency, as this will not only reduce supply chain firms' operation (production) costs but also increase their motivations to invest in green R&D, allowing them to benefit more from green R&D. In general, lower financing costs incentivize firms in the supply chain to invest in green R&D and so boost their revenues. This implies, on the one hand, that capital-constrained firms should select financing channels with the lowest interest rates, and on the other, that government regulators should take supportive measures to assist supply chain firms in lowering financing costs for green R&D.

8. Conclusion

In this study, we consider a green supply chain system, comprising an upstream firm and a downstream firm, and explore the impact of capital constraints on the green R&D decisions of the upstream firm and the profitability of the two supply chain firms under different channel power structures. The upstream firm invests in product green R&D improvement, which has a positive impact on reducing its production costs and increasing consumer demand for its products. We assume that the upstream firm is subject to capital constraint and so has the option of addressing the capital constraint problem through external financing. For the aim of this study, we propose four decision models based on whether or not the upstream firm faces capital constraints and dominates the supply chain (the UN, DN, UE and DE models). The product green R&D level and wholesale price are considered as decision variables of the upstream firm, whereas the downstream firm decides its optimal sales price or retail margin. Based on the derived equilibrium results in the proposed four game models, we first identify the conditions that the upstream firm needs to seek financing from the external channel. Following that, we investigate the impact of capital constraint, channel power structure, financing cost and cost-reducing efficiency on the upstream firm's green R&D decisions and the corresponding profitability of the supply chain. Finally, we examine the above analysis results using practice data, demonstrating whether the theoretical results in the developed decision models are consistent with the practice observation.

The main results are summarized as follows.

(1) Compared to models without capital constraints (the UN and DN models), the upstream firm has less incentive to invest in product green R&D and corresponding product production in models with capital constraints (the UE and DE models), even though it can seek financing from an external channel. This also implies that only if the upstream firm's initial capital is low enough does it have the incentive to seek financing.

(2) Regardless of whether the upstream firm dominates the supply chain or not, the level of product green R&D in models with capital constraints (the UE and DE models) is lower than in models without capital constraints (the UN and DN models), resulting in lower profitability for supply chain firms.

(3) When compared to models in which the upstream firm acts as the leader (the UN and UE models), both the product green R&D level and the downstream firm's profitability are relatively higher in models in which the downstream firm plays the role of leader (the DN and DE models), whereas whether the upstream firm's profitability is increased depends on the green R&D investment efficiency and (or) financing cost.

(4) An increase in production cost-reducing efficiency motivates the upstream firm to improve product green R&D level, which benefits the supply chain's profitability. However, increased financing costs will reduce product green R&D level and supply chain profitability, except for the upstream firm in the DE model, whose profitability will rise if its initial capital is high enough.

(5) The empirical results completely support the aforementioned theoretical results about the impact of capital constraints on green R&D and the profitability of upstream firms. The empirical results also validate the impact of financing costs on green R&D as well as the profitability of the upstream firm if the initial capital is sufficient. Unfortunately, empirical evidence does not completely support the theoretical results about the impact of channel power structures on green R&D and upstream firm profitability.

However, this study still has the following limitations, which are worth investigating in the future. First, a major limitation is that this study only discussed external financing, not alternative financing channels such as internal supply chain financing and equity financing (Udayakumar *et al.*, 2021). In the future, this study could be extended to involve various financing types at the same time, enabling researchers to investigate the influence of various financing models on green R&D. The other limitation is that all supply chain information was assumed to be complete, but in actuality, financing and demand information, among other things, may be private (Sana, 2020, 2022d). Therefore, this study may be examined under the assumption of incomplete information. Finally, this study was developed with the assumption that only the upstream firm is concerned with green R&D. The downstream firm's investment choice in green R&D may be incorporated in the future to extend this study.

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Appendix

Proof of Proposition 5

(1) Frist, we can derive $\frac{\partial S^{*ue}}{\partial r}$ and $\frac{\partial S^{*de}}{\partial r}$ as follows:

$$\frac{\partial S^{*ue}}{\partial r} = -\frac{\left(\begin{array}{c} 8k\beta a^2\lambda^2 - 4ac\lambda^3(a\delta+\lambda) + 2c^4\delta^2(1+r)^3(a\delta+\lambda)(a\delta+3\lambda) \\ +2c^2(1+r)\left[16k^2\beta^2(1+r)^2 - 3\lambda^2\left(4k\beta(1+r)+a^2\delta^2\right)+3\lambda^4\right]\} \\ -4c^3\delta(1+r)^2\left[8k\beta\lambda(1+r) - 3\lambda^3 + a\delta\left(4k(1+r)\beta - 3\lambda^2\right)\right] \end{array}\right)}{2\left\{4k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^3} < 0,$$

$$\frac{\partial S^{*de}}{\partial r} = -\frac{\left(\begin{array}{c} 2k\beta a^2\lambda^2 + c^5\delta^3(1+r)^4(a\delta+2\lambda) - c^4\delta^2(1+r)^3\left[2k\beta(1+r) - (a\delta+3\lambda)^2\right] \\ +ac\lambda^2[2k\beta(1+r) - \lambda(2a\delta+3\lambda)] \\ +c^2(1+r)\left[8k^2\beta^2(1+r)^2 - 12k\beta\lambda^2(1+r) - \lambda^2(a\delta-\lambda)(3a\delta+5\lambda)\right] \\ -2c^3(1+r)^2\delta\left(8k(1+r)\beta\lambda - 6\lambda^3 + 3a\delta\left(k(1+r)\beta-\lambda^2\right)\right) \end{array}\right\}}{4\left[4k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^3} < 0.$$

Thus, by comparing S^{*un} and S^{*ue}, we have $S^{*un} - S^{*ue} > S^{*un} - S^{*ue}\Big|_{r=0} = 0$, which implies $S^{*un} > S^{*ue}$. By comparing S^{*dn} and S^{*de}, we have $S^{*dn} - S^{*de} > S^{*dn} - S^{*de}\Big|_{r=0} = 0$, which implies $S^{*dn} > S^{*de}$.

(2) Moreover, by comparing S^{*un} and S^{*dn}, we have:

$$S^{*un} - S^{*dn} =$$

$$-\frac{k(a-c)(c\delta+\lambda)^2\left\{\begin{array}{c} c\left[32k^2\beta^2-8kc\beta\delta^2(a+2c)+c^3\delta^4(3a+c)\right] \\ +2c^2\lambda\delta\left[c\delta^2(3a+5c)-24k\beta\right] \\ +8\lambda^2\left[k\beta(a-4c)+3c^3\delta^2\right]-2c\delta\lambda^3(3a-11c)-\lambda^4(3a-7c) \end{array}\right\}}{8\left[4k\beta-(c\delta+\lambda)^2\right]^2\left[2k\beta-(c\delta+\lambda)^2\right]^2}<0,$$

which indicates that $S*^{un} < S*^{dn}$.

By comparing $S*^{ue}$ and $S*^{de}$, we have:

$$S^{*ue}-S^{*de}=$$

$$-\frac{k(a-c(1+r))(c\delta(1+r)+\lambda)^2\left\{\begin{array}{c} c^5\delta^4(1+r)^5+8ka\beta\lambda^2(1+r)+c^4\delta^3(1+r)^4(3a\delta+10\lambda) \\ -2c^2\delta(1+r)^2\left[4ak(1+r)\beta\delta+24k(1+r)\beta\lambda-11\lambda^3\right] \\ -2c^3\delta^2(1+r)^3[8k\beta(1+r)-3\lambda(a\delta+4\lambda)]-3a\lambda^4 \\ +c(1+r)\left[32k^2\beta^2(1+r)^2-32k\beta\lambda^2(1+r)-\lambda^3(6a\delta-7\lambda)\right] \end{array}\right\}}{8\left[4k\beta(1+r)-(c\delta(1+r)+\lambda)^2\right]^2\left[2k\beta(1+r)-(c\delta(1+r)+\lambda)^2\right]^2}<0,$$

which indicates that $S*^{ue} < S*^{de}$.

Proof of Proposition 6

(1) Under the upstream firm-led models with and without capital constraint, by comparing $\theta*^{un}$ and $\theta*^{ue}$, we have:

$$\theta^{*un}-\theta^{*ue}=\frac{r\left\{4ak\beta\lambda-c^3\delta^2(1+r)(a\delta+\lambda)-c\lambda^2(a\delta+\lambda)+c^2\delta[4k\beta(1+r)-\lambda(2+r)(a\delta+\lambda)]\right\}}{\left[4k\beta-(c\delta+\lambda)^2\right]\left[4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right]}>0,$$

which implies that $\theta*^{un} > \theta*^{ue}$.

By comparing π_d^{*un} and π_d^{*ue}, we have:

$$\pi_d^{*un}-\pi_d^{*ue}=\frac{k^2\beta\left\{(a-c)^2\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-(1+r)^2(a-c-cr)^2\left[4k\beta-(c\delta+\lambda)^2\right]\right\}}{\left[4k\beta-(c\delta+\lambda)^2\right]\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}>0,$$

which indicates that $\pi_d^{*un} > \pi_d^{*ue}$.

By comparing π_u^{*un} and π_u^{*ue}, we have:

$$\pi_u^{*un}-\pi_u^{*ue}=\frac{k\left\{(a-c)^2\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-(1+r)(a-c-cr)^2\left[4k\beta-(c\delta+\lambda)^2\right]\right\}}{2\left[4k\beta-(c\delta+\lambda)^2\right]\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}-rS>$$

$$\frac{k\left\{(a-c)^2\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-(1+r)(a-c-cr)^2\left[4k\beta-(c\delta+\lambda)^2\right]\right\}}{2\left[4k\beta-(c\delta+\lambda)^2\right]\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}-rS^{*ue}>0,$$

which indicates that $\pi_u^{*un} > \pi_u^{*ue}$.

(2) Under the downstream firm-led models with and without capital constraint, by comparing $\theta*^{dn}$ and $\theta*^{de}$, we have:

$$\theta^{*dn}-\theta^{*de}=\frac{(a-c)(c\delta+\lambda)\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-[a-c(1+r)][c\delta(1+r)+\lambda]\left[2k\beta-(c\delta+\lambda)^2\right]}{2\left[2k\beta-(c\delta+\lambda)^2\right]\left[2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}>0,$$

which indicates that $\theta^{*dn}>\theta^{*de}$.

By comparing π_d^{*dn} and π_d^{*de}, we have:

$$\pi_d^{*dn}-\pi_d^{*de}=\frac{k(a-c)^2\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-k(1+r)(a-c-cr)^2\left[2k\beta-(c\delta+\lambda)^2\right]}{4\left[2k\beta-(c\delta+\lambda)^2\right]\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}>0,$$

which indicates that $\pi_d^{*dn}>\pi_d^{*de}$.

By comparing π_u^{*dn} and π_u^{*de}, we have:

$$\pi_u^{*dn}-\pi_u^{*de}=\frac{k(a-c)^2\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-k(1+r)\left[2k\beta-(c\delta+\lambda)^2\right]}{8\left[2k\beta-(c\delta+\lambda)^2\right]\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}-rS>$$

$$\frac{k(a-c)^2\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}-k(1+r)\left[2k\beta-(c\delta+\lambda)^2\right]}{8\left[2k\beta-(c\delta+\lambda)^2\right]\left[2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}}-rS^{*de}>0,$$

which indicates that $\pi_u^{*dn}>\pi_u^{*de}$.

Proof of Proposition 7

(1) Under the no capital constraint models, by comparing θ^{*un} and θ^{*dn}, we have:

$$\theta^{*un}-\theta^{*dn}=-\frac{(a-c)(c\delta+\lambda)^3}{2\left[2k\beta-(c\delta+\lambda)^2\right]\left[4k\beta-(c\delta+\lambda)^2\right]}<0,$$

which indicates that $\theta^{*un}<\theta^{*dn}$.

By comparing π_d^{*un} and π_d^{*dn}, we have:

$$\pi_d^{*un}-\pi_d^{*dn}=-\frac{k(a-c)^2\left\{4k^2\beta^2+\left[2k\beta-(c\delta+\lambda)^2\right]^2\right\}}{4\left[2k\beta-(c\delta+\lambda)^2\right]\left[4k\beta-(c\delta+\lambda)^2\right]^2}<0$$

which indicates that $\pi_d^{*un}<\pi_d^{*dn}$.

By comparing π_u^{*un} and π_u^{*dn}, we have:

$$\pi_u^{*un}-\pi_u^{*dn}=\frac{k(a-c)^2\left[4k\beta-3(c\delta+\lambda)^2\right]}{8\left[2k\beta-(c\delta+\lambda)^2\right]\left[4k\beta-(c\delta+\lambda)^2\right]}.$$

which indicates that $\pi_u^{*un} > (<)\pi_u^{*dn}$ if $k > (<)\frac{3(c\delta+\lambda)^2}{4\beta}$. (2) Under the capital constraint models, by comparing θ^{*ue} and θ^{*de}, we have:

$$\theta^{*ue} - \theta^{*de} = -\frac{[a-c(1+r)][c\delta(1+r)+\lambda]^3}{2\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}} < 0,$$

which indicates that $\theta^{*ue} < \theta^{*de}$. By comparing π_d^{*ue} and π_d^{*de}, we have:

$$\pi_d^{*ue} - \pi_d^{*de} = -\frac{k(1+r)[a-c(1+r)]^2\left\{4k^2\beta^2(1+r)^2+\left[2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right]^2\right\}}{4\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^2} < 0,$$

which indicates that $\pi_d^{*ue} < \pi_d^{*de}$.

By comparing π_u^{*ue} and π_u^{*de}, we have:

$$\pi_u^{*ue} - \pi_u^{*de} = \frac{k(1+r)[a-c(1+r)]\left[4k\beta(1+r)-3(c\delta(1+r)+\lambda)^2\right]}{8\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}},$$

which indicates that $\pi_u^{*ue} > (<)\pi_u^{*de}$ if $k > (<)\frac{3(c\delta+\lambda)^2}{4\beta}$. Proof of Proposition 8. Under the upstream firm-led model with capital constraint, we can derive $\frac{\partial\theta^{*ue}}{\partial r}$, $\frac{\partial\pi_d^{*ue}}{\partial r}$ and $\frac{\partial\pi_u^{ue}}{\partial r}$ as follows:

$$\frac{\partial\theta^{*ue}}{\partial r} = -\frac{4ka\beta\lambda+4k\delta\beta c^2(1+r)-c(a\delta+\lambda)[c\delta(1+r)+\lambda]^2}{\left[4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right]^2} < 0,$$

which indicates that $\frac{\partial\theta^{vue}}{\partial r} < 0$.

$$\frac{\partial\pi_d^{*ue}}{\partial r} = -\frac{2k^2\beta(1+r)(a-c-cr)\{a[c\delta(1+r)+\lambda][\lambda-c\delta(1+r)]+2c(1+r)[2k\beta(1+r)-\lambda[c\delta(1+r)+\lambda]]\}}{\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^3} < 0,$$

which indicates that $\frac{\partial\pi_d^{*ue}}{\partial r} < 0$.

$$\frac{\partial\pi_u^{*ue}}{\partial r} = S - \frac{k(a-c-cr)\left\{a[c\delta(1+r)+\lambda][\lambda-c\delta(1+r)]+c(1+r)\left[8k(1+r)+\lambda-[c\delta(1+r)+2\lambda]^2\right]\right\}}{\left\{4k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^2} < 0,$$

which indicates that $\frac{\partial\pi_u^{ue}}{\partial r} < 0$.

Under the downstream firm-led model with capital constraint, we can derive $\frac{\partial\theta^{*de}}{\partial r}$, $\frac{\partial\pi_d^{*de}}{\partial r}$ and $\frac{\partial\pi_u^{*de}}{\partial r}$ as follows:

$$\frac{\partial\theta^{*de}}{\partial r} = \frac{-2k\beta[a\lambda+c^2\delta(1+r)]+c(a\delta+\lambda)[c\delta(1+r)+\lambda]^2}{2\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^2} < 0,$$

which indicates that $\frac{\partial\theta^{*de}}{\partial r} < 0$.

$$\frac{\partial \pi_d^{*de}}{\partial r} = -\frac{k[a-c(1+r)]\left\{c^2(1+r)^2[4k\beta - c\delta[c\delta(1+r)+\lambda] + [c\delta(1+r)+\lambda][a[c\delta(1+r)-\lambda] + 3\lambda c(1+r)]\right\}}{4\left\{2k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^2} < 0,$$

which indicates that $\frac{\partial \pi_d^{*de}}{\partial r} < 0$.

$$\frac{\partial \pi_u^{*de}}{\partial r} = S - \frac{k[a-c(1+r)]\left[c^2(1+r)^2[4k\beta - c\delta[c\delta(1+r)+\lambda] + [c\delta(1+r)+\lambda][a[c\delta(1+r)-\lambda] + 3\lambda c(1+r)]\right\}}{8\left\{2k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^2}.$$

From the above equation, let

$$S^{\#} = \frac{k[a-c(1+r)]\left[c^2(1+r)^2[4k\beta - c\delta[c\delta(1+r)+\lambda] + [c\delta(1+r)+\lambda][a[c\delta(1+r)-\lambda] + 3\lambda c(1+r)]\right\}}{8\left\{2k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^2} > 0.$$

Therefore, with $S < S^{*de}$, we can obtain that:

$$S^{*de} - S^{\#} = \frac{ck(1+r)(a-c-cr)}{4\left\{2k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}} > 0.$$

Thus, we have $\frac{\partial \pi_u^{*de}}{\partial r} > (\leq) 0$ if $S > (\leq) S^{\#}$.

Proof of Proposition 9

Under the upstream firm-led model with capital constraint, we can derive $\frac{\partial \theta^{*ue}}{\partial \delta}$, $\frac{\partial \pi_d^{*ue}}{\partial \delta}$ and $\frac{\partial \pi_u^{*ue}}{\partial \delta}$ as follows:

$$\frac{\partial \theta^{*ue}}{\partial \delta} = \frac{c(1+r)(a-c-cr)\left\{4k\beta(1+r) + [c\delta(1+r)+\lambda]^2\right\}}{\left\{4k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^2} > 0,$$

which indicates that $\frac{\partial \theta^{*ue}}{\partial \delta} > 0$.

$$\frac{\partial \pi_d^{*ue}}{\partial \delta} = \frac{4k^2 c\beta(1+r)^3(a-c-cr)^2[c\delta(1+r)+\lambda]}{\left\{4k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^3} > 0,$$

which indicates that $\frac{\partial \pi_d^{*ue}}{\partial \delta} > 0$.

$$\frac{\partial \pi_u^{ue}}{\partial \delta} = \frac{kc(1+r)^2(a-c-cr)^2[c\delta(1+r)+\lambda]}{\left\{4k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^2} > 0,$$

which indicates that $\frac{\partial \pi_u^{*ue}}{\partial \delta} > 0$.

Under the downstream firm-led model with capital constraint, we can derive $\frac{\partial \theta^{*de}}{\partial \delta}$, $\frac{\partial \pi_d^{*de}}{\partial \delta}$ and $\frac{\partial \pi_u^{de}}{\partial \delta}$ as follows:

$$\frac{\partial \theta^{*de}}{\partial \delta} = \frac{c(1+r)(a-c-cr)\left\{2k\beta(1+r) + [c\delta(1+r)+\lambda]^2\right\}}{2\left\{2k\beta(1+r) - [c\delta(1+r)+\lambda]^2\right\}^2} > 0,$$

which indicates that $\frac{\partial \theta^{*de}}{\partial \delta} > 0$.

$$\frac{\partial \pi_d^{\cdot de}}{\partial \delta} = \frac{kc(1+r)^2(a-c-cr)^2[c\delta(1+r)+\lambda]}{2\left\{2k\beta(1+r)-[c\delta(1+r)+\lambda]^2\right\}^2} > 0,$$

which indicates that $\frac{\partial \pi_d^{\cdot de}}{\partial \delta} > 0$.

$$\frac{\partial \pi_u^{*de}}{\partial \delta} = \frac{kc(1+r)^2(a-c-cr)^2[c\delta(1+r)+\lambda]}{4\left\{2k(1+r)\beta-[c(1+r)\delta+\lambda]^2\right\}^2} > 0,$$

which indicates that $\frac{\partial \pi_u^{de}}{\partial \delta} > 0$.

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