Enterprises' decision-making under government green subsidy and information asymmetry

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ABSTRACT
Environmental issues have gradually become the focus of public attention. With the increase of consumers' awareness in environmental protection, the green development of supply chain has become the mainstream trend in the foreseeable future. At this point, government subsidy in research and development becomes a non-negligible external factor in the greening of the supply chain. In order to explore the influencing mechanism of government subsidy on the supply chain under different decision situations, this paper initially constructs a model with a leading manufacturer and a subsequent retailer and then explores the optimal decisions under centralized and decentralized decision-making. Furthermore, we simulate and validate the effects of government subsidy policies on the decisions of supply chain participants. The results show that government subsidy has a positive influence on green technology improvements in the supply chain, but the incomplete utilization of government subsidy funds under information asymmetry may significantly reduce the efficiency of policy. Under information asymmetry, the actual revenues of participants will be larger than the profits in information symmetry only when the percentage of misappropriation is relatively low. Additionally, information asymmetry will lead to a decline in social welfare and is more pronounced under centralized decision making. Finally, we provide managerial and practical insights for the enterprise managers' decisions.

KEYWORDS
supply chain management; goverment subsidy; Stackelberg game; information asymmetry; decision analysis

1. Introduction

With the intensification of water and air pollution, environmental problems have become increasingly prominent, and the governments have gradually begun to focus on the problems brought about by the production process of enterprises, and to formulate laws to regulate the pollution emissions in enterprises' operations (Chekima et al. 2016; Yang and Xiao 2017). Currently, with the effective implementation of the government's production policy and the continuous promotion of green consumption, consumers' awareness of environmental protection is increasing, and they tend to pay more to the environmental-friendly products when they purchase goods, which puts

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forward higher requirements for green production by enterprises. Green production refers to a comprehensive measure that takes energy saving and pollution reduction as the goal and implements pollution control in the whole process of industrial production by means of management and technology to minimize the number of pollutants, which has become the core competitiveness of enterprises under the mainstream trend of green development (Paul 2022). Similarly, the low-carbon development and green upgrading of the supply chain have become the focus of society. Reducing the pollution emission of the whole process and improving the greenness degree of the final products can meet the low-carbon demand of consumers as well as enhance the competitiveness of the supply chain (Singh Padiyar et al. 2022).

Under the circumstance of green development, enterprises need to pay more attention to the negative impact of their manufacturing processes on the social environment (Panda 2017). In order to achieve green production as well as obtain good brand images, many core enterprises in the supply chains have positively responded to the governments call and vigorously undertaken the corporate social responsibility of improving their green level and reducing the production pollution of their products (Khan 2018; Song et al. 2020). For example, Walmart required its suppliers to participate in carbon emission disclosure projects and purchased products from suppliers who have obtained environmental certificates to ensure a reduction in environmental pollution throughout the supply chain, while Carrefour emphasized in its corporate social responsibility report that suppliers must pay more attention to the green safety of their products. It is not difficult to see that green production has become an important development strategy for business managers (Poussing 2019). In the efforts which aim to promote green production, enterprises' research and development (R&D) investment in green technology plays a significant role, which contributes to reducing environmental pollution and improving the green degree of the final products of the whole supply chain (Li and Huang 2017). Therefore, many managers are highly concerned about the innovation of green technology and heavily invest in green R&D in the production process since it is an important breakthrough point for the new round of corporate development and is also one of the core competitiveness of enterprises in the low-carbon supply chain (Li et al. 2016; Luthra et al. 2017).

Consumer demand for green products is another important driving force for companies to accelerate their internal technological innovation. In a market environment with consumers' green preferences, how to achieve green innovation in products is a major task for enterprises (Yang et al. 2020). Nowadays, managers concentrate on enterprises' green upgrading and actively promote the improvement of product technology in order to enhance the green level of products as well as the market competitiveness. Undeniably, the greening of the entire production process and the final products will obviously increase the comprehensive competitiveness of the entire supply chain, which is beneficial to all participants in the supply chain (Chen et al. 2019). Nevertheless, due to the uncertainty of technology R&D and the complexity of the social environment, the high cost of technology R&D may discourage the motivations of small and medium-sized enterprises and is therefore often borne by the core large enterprises alone (Zhu and He 2017). Additionally, the inevitable technology spillover effect which is beneficial to all participants in the supply chain will further decrease core enterprises' willingness to technology R&D and even make them feel unfair (Wang & Song 2022). The risk of sunk costs invested in failed R&D in the early stage will also inhibit the incentive of core enterprises to improve their green technology (Sinayi and Rasti-Barzoki 2018; Sun et al. 2019). Therefore, collaborative R&D becomes a common phenomenon in green upgrading of supply chains. Compared with the individual R&D by core enterprises under decentralized decision-making, cooperative R&D of upstream and downstream enterprises under centralized decision-making can simultaneously achieve the improvement of each profit and the greening upgrading of products (Jamali and Rasti-Barzoki 2018). Coordination and cooperation between upstream and downstream enterprises can be achieved through contracts such as cost-sharing, revenue-sharing, and two-part tariffs, which gradually becomes a tendency for the supply chains' green development (?Song and Gao 2018; Toktas-Palut 2021).

Consumer demand for green products is an important driving force for companies to accelerate their internal technological innovation. In a market environment with green preferences, how to achieve green innovation in products and cater consumer demands has become a major task for enterprise managers (Yang et al. 2020). Nowadays, managers concentrate on the green upgrades of enterprises and actively promote the improvement of product technology in order to enhance the green level of products as well as the market competitiveness. Undeniably, the greening of the entire production process and the final products will obviously increase the comprehensive competitiveness of the entire supply chain, which is beneficial to all participants in the supply chain. Nevertheless, due to the uncertainty of technology R&D and the complexity of the social environment, the high cost of technology R&D may discourage the motivations of small and medium-sized enterprises, and is therefore often borne by the core large enterprises alone (Zhu and He 2017). Additionally, the inevitable technology spillover effect which is beneficial to all participants in the supply chain, will further decrease core enterprises' willingness in technology R&D and even make them feel unfair (Chen et al. 2019). The risky of sunk costs invested in failed R&D in the early stage will also inhibit the incentive of core enterprises to improve their green technology (Sinayi and Rasti-Barzoki 2018; Sun et al. 2019). Therefore, collaborative R&D becomes a common phenomenon in green upgrading of supply chains. Compared with the individual R&D by core enterprises under decentralized decision making, cooperative R&D of upstream and downstream enterprises under centralized decision making can simultaneously achieve the improvement of each profit and the greening upgrading of products (Jamali and Rasti-Barzoki 2018). Coordination and cooperation between upstream and downstream enterprises can be achieved through contracts such as cost-sharing, revenue-sharing, and two-part tariffs, which gradually becomes a tendency for the supply chains' green development (Song and Gao 2018; Toktas-Palut 2021).

Cooperative R&D between upstream and downstream enterprises is a non-negligible internal driving force for supply chains' greening and upgrading, while government subsidy policy is an important external boosting factor. In order to decrease the R&D pressure as well as to increase the financial strength of technology investment, governments will provide preferential policies such as R&D subsidies, lower taxes and other incentives and these policies usually will have different effects in the scenarios of decentralized and centralized decision-making in the supply chain (Wang et al. 2017; Chen et al. 2020). In the beginning, these preferential policies are designed to reduce the financial pressure on enterprises for green technology R&D and to further promote the upgrading of the entire supply chain. However, due to the complexity of the information environment, the subsidy policies may have many practical problems such as underutilization and over-subsidization (Genovese et al. 2017; Qin and Shao 2019). For example, since 2020, the Chinese government has strongly supported the development of green energy vehicles (hybrid electric vehicles, battery-only electric vehicles, fuel cell electric vehicles) with a huge share of subsidies for the R&D and production of the manufacturers. Nevertheless, due to the information asymmetry between the government and enterprises, many small and medium-sized enterprises have diverted the governments' subsidies to their daily production and operation expenses, making the utility of government subsidies greatly reduced, not to mention the development of the new energy vehicle industry. Incomplete information symmetry between the government and supply chain enterprises is a common phenomenon in the information age, which not only affects the strategic decisions within the enterprises but also affects the efficiency of government subsidy policies (Song et al. 2020). Additionally, scholars also explored the impact of government subsidies on social welfare (Ji et al. 2017; Wang et al. 2017). It is generally agreed that government subsidy is an important influencing factor in social welfare and different subsidy strategies should be offered under different market structures (Shao et al. 2017; Hafezalkotob 2018b). Currently, there are many studies on information asymmetry between firms within the supply chain, while there are fewer studies on information asymmetry between government and supply chain firms. Moreover, existing studies usually assume that government subsidies for technology R&D can fully meet the expected effects, which is too idealistic and does not correspond to the realistic situation (Madani and Rasti-Barzoki 2017; Zhao and Sun 2020). Therefore, it is of great significance to study the impact of information asymmetry on government subsidy policies and social welfare.

The green development of supply chains has become a current trend, but few scholars have studied the impact of the government's green subsidy policy on supply chain members under information asymmetry. Based on this, this paper constructs a game model for a supply chain with one leading manufacturer and one following retailer under an asymmetric information environment. We respectively analyze the impact of the government's green R&D subsidy on enterprises' pricing decisions from two perspectives of decentralized decision-making and centralized decision-making. The impact of consumers' price preference and green preference on the game equilibrium is also analyzed. In addition, we further compare and analyze the differences in the game equilibrium in different situations, and further explore the impact of information asymmetry on the overall social welfare. Finally, some recommendations are provided for the implementation of government subsidy policies. The remainder of the paper is organized as follows. The related literature is reviewed in Section 2. The optimal solutions for a supply chain under anarchy, information symmetry, and information asymmetry are calculated in Section 3. The comparative analysis in different situations is presented in Section 4. A simulation of government subsidies under information asymmetry is discussed in Section 5. The key conclusions and some management insights are drawn in Section 6.

2. Literature review

Green and sustainable development has currently become the mainstream trend in supply chain enterprises. Since traditional supply chains may have serious pollution emissions in their upstream, midstream, and downstream enterprises, how to decrease the pollution in the production process and increase the green performance of final products is a key part of the supply chains' greenness upgrading (Tharani & Uthayakumar 2020). Li et al. (2016a) introduced green management into e-commerce supply chains and found that when the greening costs were relatively high, green R&D investment was not an ideal choice for enterprises. However, when the loyalty of customers to the supply chain was high and the greening cost met certain conditions, the green strategy would have greater benefits. Li et al. (2016b) analyzed survey data collected from 256

Chinese high-tech enterprises and found that green product design and green supply chain processes were greatly beneficial for enterprises' financial performance. Chen et al. (2019) believed that the degree of improvement of the green technology R&D cooperation among supply chain enterprises on their economic performance mainly depended on their level of green contribution. And when supply chain companies had higher green R&D investment efficiency and spillover effects, the improvement in enterprise performance was more obvious. Genovese et al. (2017) conducted research on the development of the chemical and food industries and found that if supply chain enterprises incorporate environmental utility into their strategies and pay attention to their carbon emissions, it would advance the circular development of the economy and enhance the competitiveness of the entire supply chain. The abovementioned studies generally believe that the innovation of green technology within supply chain enterprises is beneficial to improving the performance of enterprises and is conducive to the sustainable development of supply chains in the long term. Therefore, how to better improve the level of green technology of supply chain enterprises' production processes and final products and then further promote the sustainable development of supply chains, has currently become the main problem faced by enterprise managers.

Green technology R&D in the production process is a significant driver to improve the greening of the supply chain, thus a large number of literatures have studied this area. As an important basic method, game theory is widely used by scholars to analyze and discuss the strategies of participants in the supply chain (Hafezalkotob 2018a). Sun et al. (2019) constructed a two-echelon game model consisting of a manufacturer and a retailer and found that the manufacturer's R&D activity was beneficial to the low-carbon development of the whole supply chain. Yu et al. (2016) also established a game model with a manufacturer and a retailer and believed that consumers environmental awareness would encourage manufacturers to produce more green products with higher green levels. Enterprises' green R&D could not only meet the mainstream demand of consumers, but also further increase the market competitiveness of the whole supply chain. Different from the research of Sun et al. (2019) and Yu et al. (2016), Wu, et al. (2021) built a supply chain composed of two suppliers and one manufacturer and comprehensively considered the situation of the manufacturer's independent R&D, joint R&D with one supplier, and joint R&D with two suppliers. The results showed that there was an obvious technology spillover effect in the manufacturer's green technology R&D, and the benefits of the whole supply chain achieved the greatest when the manufacturer cooperated with two suppliers. Although the abovementioned literature recognizes the important role of enterprises' R&D in the supply chains' green development based on the game theory, the above-mentioned documents do not mention the government's green subsidies to enterprises, which often have a significant impact on the strategic decisions of enterprises.

As a common means of intervention, the government's green subsidy is a critical external motivation, which is beneficial to reducing the pressure on enterprises' green R&D as well as to increasing the capital in green R&D investment (Zhang and Yousaf 2020). Policies such as fiscal appropriations, lower interest rates, and tax rebates will provide enterprises with a better economic environment for their green technology R&D. In view of the strategic significance of government preferential policies to the development of supply chains, many scholars have thoroughly assessed the impact of subsidy policies on the enterprises. Wu et al. (2019) constructed a game model of a closed-loop supply chain and investigated the optimal decision of the channel members under different subsidy ratios. They found that government subsidies can effectively encourage enterprises to upgrade their level of green technology and improve the overall economic benefits of the supply chain. Yang and Xiao (2017) suggested that when government intervention increased, the green level of products would increase while retail prices increasing or decreasing depended on the leading position of the manufacturers and retailers. Furthermore, some scholars discussed the impact of government subsidy on social welfare, Liu et al.(2019) emphasized that government subsidies will contribute to a higher level of corporate social responsibility and achieve larger overall social welfare. Qu et al., (2019) indicated that a higher government green subsidy offered to the manufacturer can lead to a higher social welfare while a higher government green subsidy provided to the retailer may cause a lower social welfare. Hence, how government policy affects social welfare is also an important issue which is worth of analysis. The aforementioned research shows that government subsidy has a non-negligible influence on channel members decisions and social welfare. However, these literatures are all based on information symmetry between the government and the enterprises and assume that subsidy policies can be completely effective by default. This is not completely in line with the actual situation. Information asymmetry is a more common phenomenon in the real environment. Thereby, it is of practical significance to consider the efficiency of subsidies when information asymmetry exists (Ma, Shang, and Wang 2017; Shen et al. 2019).

In fact, information asymmetry is a common phenomenon, which has an obvious influence on the strategic decision-making of enterprises (Du et al. 2020). Because of information asymmetry between decision makers, it will lead to an increase of the information costs in the supply chain. Although some of the enterprises may benefit from the information asymmetry, the overall revenue of a supply chain usually tends to decrease (Song and Gao 2018). Liu et al. (2019) stressed the importance of information costs in the current economic environment. By comparing the decision-making effect under asymmetric information and symmetric information, they suggested that the profits of channel members under symmetric information were much better, which meaned that the development of supply chain enterprises were more effective in the environment of information disclosure. Wu et al. (2017) constructed an asymmetric supply chain model in which retailers understand the heterogeneity of customers but suppliers did not. They agreed that it was difficult for suppliers and retailers to achieve two-part tariff coordination under asymmetric information. Visibly, information asymmetry not only had a significant influence on the strategic decision-making between the enterprises in a supply chain, but it also affected the efficiency of the governments subsidy policy for supply chain enterprises. Therefore, the policy may not achieve the expected effects when it is implemented (Lai et al. 2018). Wu et al. (2019) argued that increased competition and information asymmetry among firms would affect the composition of profits and the distribution of profits among firms may weaken the effect of government subsidies. Li et al. (2019) constructed a supply chain composed of one manufacturer and one supplier and considered moral hazard and adverse selection issues between the government and manufacturers. Hu et al. (2019) developed a model that includes government and recycling firms in double information asymmetry. Their study showed that under information asymmetry, the governments' subsidy policy for high-tech recyclers was relatively stable under different circumstances, but the misreporting of information from low-tech recyclers may cause large fluctuations in the subsidy efficiency. It can be seen from the abovementioned literature that information asymmetry is the prevailing state of the current economic environment, which often affects the strategic decision-making of enterprises. The information asymmetry between the government and supply chains also causes the government subsidy policy to fail to optimize the result and reduces the effectiveness of policies. However, there are few studies on government subsidy policies under information asymmetry between the government and a supply chain in the existing literature. Additionally, these studies tend to by default assume information symmetry between the government and supply chains so that the governments subsidies can be completely idealized, which is not in line with the economic reality. Therefore, it is of great practical significance to analyze he impact of government subsidies on the strategies of manufacturers and retailers in both decentralized decision-making and centralized decision-making and to further explore the impact of the information environment on the effectiveness of government subsidy policies.

Based on this, this article constructs a two-echelon supply chain with a leading manufacturer and a following retailer. Then, we analyze the impact of the government's green subsidy policy on the game equilibrium in decision-making status of decentralization and centralization, and information environment of information symmetry and information asymmetry. And then we comparatively analyze the difference of game equilibrium between these states. Our study aims to discuss the following issues: (1) In the environment of government green R&D subsidies, what is the optimal decision for the supply chain in decentralized and centralized decision-making situations? (2) Is the government subsidy policy more effective in a centralized or decentralized decision-making environment? (3) How do consumers' price preferences and green preferences affect the optimal decisions of supply chain companies? (4) How does the information environment between the government and the supply chain affect the optimal decision-making of supply chain enterprises? (5) What is the impact of information asymmetry on the efficiency of government subsidies and social welfare? Through the research of the abovementioned issues, we will further provide targeted suggestions on the implementation of government policies based on the research results.

3. Model and analysis

When game theory is applied to supply chain management, the literature tends to find a stable equilibrium under the strategies of multiple players by setting initial functions such as price function, demand function, utility function, etc., and making sequential strategic decisions through the game sequence among multiple players. Since profitability is the main goal of enterprises, scholars tend to take profit maximization or efficiency maximization as the desired output of the objective function in the research related to supply chain management. Similarly, in our work, we assume that there is a supply chain system composed of a manufacturer and a retailer, where the manufacturer is the leader in strategic decision-making. The market demand function is $Q = \alpha - \beta P + \gamma\sqrt{G}$ (Raza, 2018), of which α, β and γ $(\alpha, \beta, \gamma > 0)$ respectively represent the highest market price, the price parameter and the greenness parameter, and Q, P, and G respectively represent the product's demand, product's price and investment in green technology R&D. From the demand function, it can be seen that there is an aggregate market α. An increase in the market price of the product P will lead to a decrease in consumer demand while an increase in the greenness of the product G will lead to an increase in consumer demand, which is consistent with the real economic environment. C_m and C_r are the unit cost of the manufacturer and unit cost of the retailer. In order to ensure the profitability of the enterprises, we assign that the wholesale price at which the manufacturer sells to the retailer is ω $(\omega \geq C_m)$ and the retail price at which the retailer sells to the consumer is P $(P \geq \omega + C_r)$. In reality, although green products have the advantages of environmental friendliness, low energy consumption, and low emissions, some consumers are still more sensitive to price than green performance when purchasing some products. In addition, since the R&D investment of enterprises is often affected by various factors such as policy, environment, technology, etc., there must be an upper limit on investment. Similarly, to ensure the concavity and convexity of the function, we assume that $8\beta > 5\gamma^2$ and $G \leq [\frac{2\beta(\omega - C_m)}{\gamma}]^2$. When entities make strategic decisions, they can choose to seek to maximize their personal interests and make independent decisions or choose to make joint decisions to maximize the benefits of the overall supply chain. Therefore, this article analyzes the game equilibrium of the supply chain under decentralized and centralized decision-making. Under decentralized decision-making, the manufacturer, as the leader in the supply chain, makes the first decision, and the retailer makes subsequent decisions based on the manufacturer's decision. They both pursue the maximization of their personal interests. In the case of centralized decision-making, manufacturers and retailers make strategic decisions as a whole to maximize the benefits of the overall supply chain. To facilitate the derivation of the subsequent equations, the parameters are listed in tab. 1.

Table 1. Description of different parameters

Parameters	Description
α	Highest market price
β	Price parameter
γ	Green parameter
G	Total investment in green R&D
m, r, sc, g	Subscripts of the manufacturer, retailer, supply chain and government
c, d	Superscript for centralized and decentralized decision-making
$\wedge, \sim$	Superscripts of information symmetry and information asymmetry
ω	Unit wholesale price sold by the manufacturer to the retailer
P	Unit retail price sold by the manufacturer to consumers
Q	Demand of the products
π	Profits of the manufacturer and the retailer
λ	Proportion of green R&D undertaken by the supply chain
SW	Social welfare
τ	Proportion of government subsidy actually spend on green R&D
T	Amount of government subsidies spent on green R&D under information asymmetry

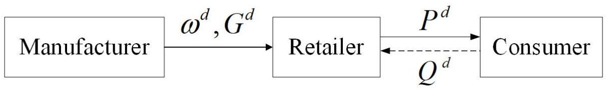
3.1. *Under anarchy*

Initially, we analyze the game equilibrium without government subsidy. As the manufacturer is the leader in the decision-making process when the manufacturer and the retailer choose to make decentralized decisions, the manufacturer first determines the wholesale price ω^d and green R&D investment G^d, and then the retailer determines the retail price P^d according to the manufacturer's strategy. Simultaneously, the retail price and green R&D investment have a significant influence on consumers' market demand Q^d. The game sequence of the manufacturer and retailer under decentralized decision-making is shown in fig. 1(a). At this point, the profit functions of the manufacturer and retailer respectively are:

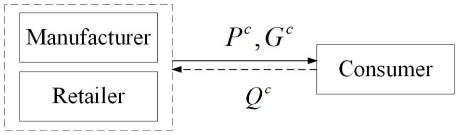
$$\pi_m^d = (\omega^d - C_m)(\alpha - \beta P^d + \gamma\sqrt{G^d}) - G^d, \tag{1}$$

$$\pi_r^d = (P^d - \omega^d - C_r)(\alpha - \beta P^d + \gamma\sqrt{G^d}). \tag{2}$$

Under decentralized decision-making, the manufacturer is the first mover and the retailer makes the strategy based on the manufacturer's action. According to their



(a) Decentralized decision-making



(b) Centralized decision-making

Figure 1. Game sequences without government subsidies

game sequence and the basic solution method of the game model, we solve the game in reverse. Let $\frac{\partial \pi_r^d}{\partial P^d} = 0$ and then obtain $P^d = \frac{\alpha+\gamma\sqrt{G^d}+\beta(\omega^d+C_r)}{2\beta}$. Then, we substitute P^d into equation (1) and obtain function π_m^d. At this time, the Hessian matrix of π_m^d with respect to ω_d and G_d is $H = \begin{bmatrix} \frac{\partial \pi_m^{d\,2}}{\partial^2 \omega^d} & \frac{\partial \pi_m^{d\,2}}{\partial \omega^d \partial G^d} \\ \frac{\partial \pi_m^{d\,2}}{\partial G^d \partial \omega^d} & \frac{\partial \pi_m^{d\,2}}{\partial^2 G^d} \end{bmatrix} = \begin{bmatrix} -\beta & \frac{\gamma}{4G^{d\frac{1}{2}}} \\ \frac{\gamma}{4G^{d\frac{1}{2}}} & -\frac{\gamma(\omega^d - C_m)}{8G^{d\frac{3}{2}}} \end{bmatrix}$. Since $G \leq [\frac{2\beta(\omega - C_m)}{\gamma}]^2$, the inequality of $|H| = \frac{\gamma}{16G^{d\frac{3}{2}}}[\frac{2\beta(\omega^d - C_m)}{\gamma} - G^{d\frac{1}{2}}] \geq 0$ holds. Additionally, due to $\beta > 0$, we can obtain that the Hessian matrix is negative definite, and the function has a maximum value with respect to ω_d and G_d. Thus, we let $\frac{\partial \pi_m^d}{\partial G^d} = 0$ and $\frac{\partial \pi_m^d}{\partial \omega^d} = 0$, obtaining $\omega^d = \frac{4\alpha - \gamma^2 C_m + 4\beta(C_m - C_r)}{8\beta - \gamma^2}$ and $\sqrt{G^d} = \frac{\gamma[\alpha - \beta(C_m + C_r)]}{8\beta - \gamma^2}$. Therefore, the retail price, market output, manufacturer's profit, and retailer's profit respectively are:

$$P^d = \frac{6\alpha + (2\beta - \gamma^2)(C_m + C_r)}{8\beta - \gamma^2}, \quad Q^d = \frac{2\beta[(\alpha - \beta(C_m + C_r)]}{8\beta - \gamma^2}, \tag{3}$$

$$\pi_m^d = \frac{[(\alpha - \beta(C_m + C_r)]^2}{8\beta - \gamma^2}, \quad \pi_r^d = \frac{4\beta[(\alpha - \beta(C_m + C_r)]^2}{(8\beta - \gamma^2)^2}. \tag{4}$$

When the manufacturer and retailer cooperate in centralized decision-making, they will take maximizing the benefits of the entire supply chain as a common goal and jointly determine the retail price and green R&D investment. Specifically, the manufacturer and retailer cooperatively decide the green R&D investment G^c and the retail price P^c, which will influence consumers' demand Q^c. The game sequence of the manufacturer and retailer under centralized decision-making is shown in fig. 1(b). At this point, the profit of the overall supply chain is:

$$\pi_{sc}^c = (P^c - C_m - C_r)(\alpha - \beta P^c + \gamma\sqrt{G^c}) - G^c. \tag{5}$$

Under centralized decision-making, the Hessian matrix of π_{sc}^c with respect to P_c and G_c is $H = \begin{bmatrix} -2\beta & \frac{\gamma}{2G^{c\frac{1}{2}}} \\ \frac{\gamma}{2G^{c\frac{1}{2}}} & -\frac{\gamma(P^c - C_m - C_r)}{4G^{c\frac{3}{2}}} \end{bmatrix}$. Thereby, the determinant of the matrix is $|H| = \frac{\gamma[2\beta(P^c - C_m - C_r) - \gamma\sqrt{G^c}]}{4G^{c\frac{3}{2}}}$. Due to $G \leq [\frac{2\beta(\omega - C_m)}{\gamma}]^2$ and $P^c \geq \omega + C_r$, the inequaity of $\gamma\sqrt{G^c} \leq 2\beta(\omega^c - C_m) \leq 2\beta(P^c - C_m - C_r)$ holds. Thus, the Hessian matrix is negative definite and there is a maximum value with respect to P_c and G_c. We let $\frac{\partial \pi_{sc}^c}{\partial P^c} = 0$, $\frac{\partial \pi_{sc}^c}{\partial G^c} = 0$ and obtain $P^c = \frac{2\alpha + (2\beta - \gamma^2)(C_m + C_r)}{4\beta - \gamma^2}$, $\sqrt{G^c} = \frac{\alpha - \beta(C_m + C_r)}{4\beta - \gamma^2}$. Therefore, when the game is in equilibrium, the optimal output of the overall supply chain and the optimal profit of the supply chain respectively are:

$$Q^c = \frac{2\beta[\alpha - \beta(C_m + C_r)]}{4\beta - \gamma^2}, \pi_{sc}^c = \frac{[\alpha - \beta(C_m + C_r)]^2}{4\beta - \gamma^2}. \tag{6}$$

Proposition 1. Without the government's subsidy, regardless of whether the manufacturer and the retailer make decentralized or centralized decisions, the optimal retail price, market output, and green R&D investment will increase with the decrease of β and with the increase of γ.

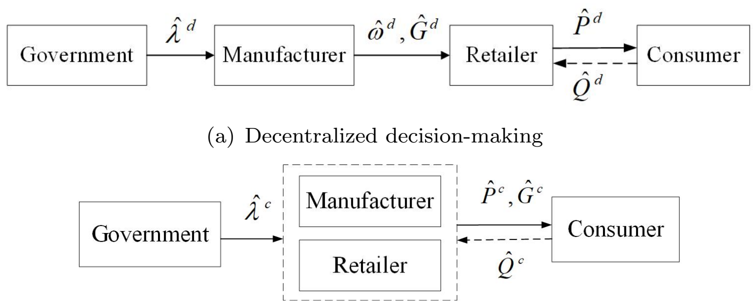
The proof process of **Proposition 1** is in the appendix, and other propositions in the following paragraphs are the same. It can be seen from **Proposition 1** that regardless of whether the manufacturer and the retailer make decentralized or centralized decisions, the price parameter has a negative effect on the equilibrium outcome while the green parameter has a positive effect. The green R&D of the supply chain falls when consumers' price preferences are high, while their profits rise when consumers' green preferences are high. Obviously, in a consumer environment with green preferences, it is beneficial for both the manufacturer and retailer when consumers have high green preferences for products.

3.2. *Government subsidy under information symmetry*

The green development of products is the mainstream trend, which is also of great significance to social development over the long run and is also a direction that the government vigorously promotes. However, green product technology takes a long time to overcome large investments. Due to the uncertainty of technical R&D, it may inhibit the willingness of small and medium-sized enterprises to invest in greenness. Hence, the government usually will support the green R&D of enterprises in the form of green subsidies, which greatly reduce the pressure on enterprises and further increase their investment in green technology R&D. In our study, we assume that the government subsidizes enterprises' green technology investment in a proportional manner and the ratio of government subsidies is $1-\lambda$. Thus, the overall green technology investment in the supply chain drops to λG. As a policy of economic intervention, the government's subsidy aims to maximize the entire utility of society. In this paper, we refer to the research of Panda et al. (2017) and use the marginal profits of manufacturers and retailers plus the consumer surplus minus government subsidies to represent social welfare, where consumer plus is denoted as follows.

$$CS = \int_{P_{min}}^{P_{max}} Q(P)dP = \frac{(\alpha - \beta P + \gamma\sqrt{G})^2}{2\beta} \tag{7}$$

In the case of the government providing subsidies, if the manufacturer and retailer conduct decentralized decision-making, the three-party game sequence is that the government first determines the proportion of subsidies $\hat{\lambda}^d$ to the manufacturer, then the manufacturer determines its R&D investment $\hat{G}^c$ and the wholesale price $\hat{\omega}^d$, and finally the retailer determines the retail price $\hat{P}^d$ of the product. The game sequence of the manufacturer, the retailer, and the government under decentralized decision-making is shown in fig. 2(a). At this time, the government's utility and the profit of the manufacturer and retailer are respectively:



(a) Decentralized decision-making

(b) Centralized decision-making

Figure 2. Game sequences with government subsidies

$$\widehat{SW}_g^d = (\hat{P}^d - C_m - C_r)(\alpha - \beta\hat{P}^d + \gamma\sqrt{\hat{G}^d}) + \frac{(\alpha - \beta P^d + \gamma\sqrt{G^d})^2}{2\beta} - (1 - \hat{\lambda}^d)\hat{G}^d, \quad (8)$$

$$\hat{\pi}_m^d = (\hat{\omega}^d - C_m)(\alpha - \beta\hat{P}^d + \gamma\sqrt{\hat{G}^d}) - \hat{\lambda}^d\hat{G}^d, \quad (9)$$

$$\hat{\pi}_r^d = (\hat{P}^d - \hat{\omega}^d - C_r)(\alpha - \beta\hat{P}^d + \gamma\sqrt{\hat{G}^d}). \quad (10)$$

Since the derivation method of under government subsidy is similar to that under anarchy, the proof processes will not be repeated here and later. The specific proof processes are in the appendix. Solving the game sequence in reverse, we obtain that game equilibrium is $\hat{\omega}^d = \frac{4\hat{\lambda}^d\alpha - \gamma^2 C_m + 4\hat{\lambda}^d\beta(C_m - C_r)}{8\hat{\lambda}^d\beta - \gamma^2}$ and $\sqrt{\hat{G}^d} = \frac{\gamma[\alpha - \beta(C_m + C_r)]}{8\hat{\lambda}^d\beta - \gamma^2}$, where $\hat{\lambda}^d = \frac{4}{9} - \frac{\gamma^2}{36\beta}$. Therefore, The product retail price, product output, profits of the manufacturer and retailer, and government subsidy amount are respectively:

$$\hat{P}^d = \frac{\beta(16\beta - 19\gamma^2)(C_m + C_r) + \alpha(48\beta - 3\gamma^2)}{2\beta(32\beta - 11\gamma^2)}, \hat{Q}^d = \frac{(16\beta - \gamma^2)[\alpha - \beta(C_m + C_r)]}{2(32\beta - 11\gamma^2)}, \quad (11)$$

$$\hat{\pi}_m^d = \frac{(16\beta - \gamma^2)[\alpha - \beta(C_m + C_r)]^2}{4\beta(32\beta - 11\gamma^2)}, \hat{\pi}_r^d = \frac{(16\beta - \gamma^2)^2[\alpha - \beta(C_m + C_r)]^2}{4\beta(32\beta - 11\gamma^2)^2}, \quad (12)$$

$$\hat{T}^d = \frac{9\gamma^2(20\beta + \gamma)[(\alpha - \beta(C_m + C_r)]^2}{4\beta(32\beta - 11\gamma^2)}. \quad (13)$$

When the manufacturer and retailer make centralized decisions with government subsidies under information symmetry, the game sequence is that the government first determines the proportion of subsidies $\hat{\lambda}^c$ to the overall supply chain, and then the overall supply chain determines R&D investment $\hat{G}^c$ and the retail price $\hat{P}^c$. The game sequence of the manufacturer, the retailer, and the government under centralized decision-making is shown in fig. 2(b). At this time, the government's utility and the overall profit of the supply chain are as follows:

$$\widehat{SW}_g^c = (\hat{P}^c - C_m - C_r)(\alpha - \beta\hat{P}^c + \gamma\sqrt{\hat{G}^c}) + \frac{(\alpha - \beta\hat{P}^c + \gamma\sqrt{\hat{G}^c})^2}{2\beta} - (1 - \hat{\lambda}^c)\hat{G}^c, \quad (14)$$

$$\hat{\pi}_{sc}^c = (\hat{P}^c - C_m - C_r)(\alpha - \beta\hat{P}^c + \gamma\sqrt{\hat{G}^c}) - \hat{\lambda}^c\hat{G}^c. \quad (15)$$

At this time, the game equilibrium is $\hat{P}^c = \frac{2\hat{\lambda}^c\alpha+(2\hat{\lambda}^c\beta-\gamma^2)(C_m+C_r)}{8\hat{\lambda}^d\beta-\gamma^2}$ and $\sqrt{\hat{G}^c} = \frac{\gamma[\alpha-\beta(C_m+C_r)]}{5\hat{\lambda}^c\beta-\gamma^2}$, where $\hat{\lambda}^c = \frac{1}{2} - \frac{\gamma^2}{16\beta}$. Therefore, the product retail price, product output, profits of the supply chain, and government subsidy amount are respectively:

$$\hat{P}^c = \frac{4\beta(16\beta - 19\gamma^2)(C_m + C_r) + 9\alpha(8\beta - \gamma^2)}{18\beta(8\beta - 5\gamma^2)}, \hat{Q}^c = \frac{(8\beta - \gamma^2)[\alpha - \beta(C_m + C_r)]}{2(8\beta - 5\gamma^2)}, \tag{16}$$

$$\hat{\pi}^c_{sc} = \frac{(8\beta - \gamma^2)[\alpha - \beta(C_m + C_r)]^2}{4\beta(8\beta - 5\gamma^2)}, \hat{T}^c = \frac{\gamma^2(8\beta + \gamma^2)[\alpha - \beta(C_m + C_r)]^2}{\beta[(8\beta - 5\gamma^2)]^2}. \tag{17}$$

Proposition 2. Under information symmetry, government subsidy only influences the game equilibrium, while the optimal retail price, market output, and green R&D investment will still increase with the decrease of β and with the increase of γ, regardless of decentralized or centralized decision-making.

Similar to the conclusion in **Proposition 1**, we can find that in a consumer environment with green preferences, government subsidy inevitably affects the game equilibrium. However, the price parameter and green preference parameter still are two key factors that affect consumers' purchase of products.

3.3. *Government subsidies under information asymmetry*

The intention of the government when subsidizing enterprises' green R&D investment is to reduce the pressure on enterprises brought about by greenness R&D. The government hopes that subsidies can promote green transformation, upgrade product performance and improve the core competitiveness of products. However, due to the information asymmetry, enterprises in the supply chain do not necessarily apply all government subsidies for product technology R&D. In addition, because a large number of small and medium-sized enterprises have financing difficulties and high capital turnover, these enterprises may use part of the government subsidy funds for their own financing and operations, which greatly reduces the efficiency of the government's subsidy policy. Suppose the actual government subsidy amount at this time is $\tau(1-\lambda)G$, where $\tau > 1$. $\frac{1}{\tau}$ represents the proportion of capital utilization, and the smaller the value is, the more enterprises invest funds in nonrelated aspects. This reflects the uncertainty when enterprises undertake social responsibility for green technology R&D under asymmetric information. The game sequence of the manufacturer, the retailer, and the government is similar to that under information symmetry. When the manufacturer and retailer choose decentralized decision-making, the government's utility and the manufacturer's and retailer's profit are as follows:

$$\widetilde{SW}^d_g = (\tilde{P}^d - C_m - C_r)(\alpha - \beta\tilde{P}^d + \gamma\sqrt{\tilde{G}^d}) + \frac{(\alpha - \beta P^d + \gamma\sqrt{\tilde{G}^d})^2}{2\beta} - \tau(1-\tilde{\lambda}^d)\tilde{G}^d, \tag{18}$$

$$\tilde{\pi}^d_m = (\tilde{\omega}^d - C_m)(\alpha - \beta\tilde{P}^d + \gamma\sqrt{\tilde{G}^d}) - \tilde{\lambda}^d\tilde{G}^d, \tag{19}$$

$$\hat{\pi}^d_r = (\tilde{P}^d - \tilde{\omega}^d - C_r)(\alpha - \beta\tilde{P}^d + \gamma\sqrt{\tilde{G}^d}). \tag{20}$$

Similar to the above proof process, we can obtain that the game equilibrium is $\tilde{P}^d = \frac{\alpha+\gamma\sqrt{\tilde{G}^d+\beta(\tilde{\omega}^d+C_r)}}{2\beta}$, $\tilde{\omega}^d = \frac{4\tilde{\lambda}^d-\gamma^2C_m+4\tilde{\lambda}^d\beta(C_m-C_r)}{8\tilde{\lambda}^d\beta-\gamma^2}$, $\sqrt{\tilde{G}^d} = \frac{\gamma[\alpha-\beta(C_m+C_r)]}{8\tilde{\lambda}^d\beta-\gamma^2}$, and $\tilde{\lambda}^d =$

$\frac{\tau(16\beta-\gamma^2)}{4\beta(7+2\tau)}$. At this time, the retailer price, product output, profits of the manufacturer and retailer, total greenness investment and government subsidy are as follows:

$$\tilde{P}^d = \frac{\alpha\tau(48\beta-3\gamma^2)+\beta[16\tau\beta-(14+5\tau)\gamma^2](C_m+C_r)}{2\beta[32\tau\beta-(7+4\tau)\gamma^2]}, \tilde{Q}^d = \frac{\tau(16\beta-\gamma^2)[\alpha-(C_m+C_r)]^2}{2\beta[32\tau\beta-(7+4\tau)\gamma^2]}, \tag{21}$$

$$\tilde{\pi}_m^d = \frac{\tau(16\beta-\gamma^2)[\alpha-(C_m+C_r)]}{4\beta[32\tau\beta-(7+4\tau)\gamma^2]}, \tilde{\pi}_r^d = \frac{\tau^2(16\beta-\gamma^2)^2[\alpha-(C_m+C_r)]^2}{4\beta[32\tau\beta-(7+4\tau)\gamma^2]^2}, \tag{22}$$

$$\tilde{G}^d = \frac{\tau^2(16\beta-\gamma^2)^2[\alpha-(C_m+C_r)]^2}{[32\tau\beta-(7+4\tau)\gamma^2]^2}, \tilde{T}^d = \frac{\tau(7+2\tau)\gamma^2[4\beta(7-2\tau)+\tau\gamma^2][\alpha-(C_m+C_r)]^2}{4\beta[32\tau\beta-(7+4\tau)\gamma^2]^2}. \tag{23}$$

When the manufacturer and retailer choose centralized decision-making, the government's utility function and the overall supply chain profit function are as follows:

$$\widetilde{SW}_g^c = (\tilde{P}^c-C_m-C_r)(\alpha-\beta\tilde{P}^c+\gamma\sqrt{\tilde{G}^c})+\frac{(\alpha-\beta P^c+\gamma\sqrt{\tilde{G}^c})^2}{2\beta}-\tau(1-\tilde{\lambda}^c)\tilde{G}^c, \tag{24}$$

$$\tilde{\pi}_{sc}^d = (\tilde{P}^c-C_m-C_r)(\alpha-\beta\tilde{P}^c+\gamma\sqrt{\tilde{G}^c})-\tilde{\lambda}^c\tilde{G}^c. \tag{25}$$

In this case, the retailer price, product output, profits of the supply chain, total greenness investment and government subsidy are as follows:

$$\tilde{P}^c = \frac{\alpha\tau(8\beta-\gamma^2)+\beta[8\beta-3(2+\tau)\gamma^2](C_m+C_r)}{2\beta[8\tau\beta-(3+2\tau)\gamma^2]}, \tilde{Q}^c = \frac{\tau(8\beta-\gamma^2)[\alpha-\beta(C_m+C_r)]}{2\beta[8\tau\beta-(3+2\tau)\gamma^2]}, \tag{26}$$

$$\tilde{\pi}_{sc}^c = \frac{\tau(8\beta-\gamma^2)[\alpha-\beta(C_m+C_r)]^2}{4\beta[8\tau\beta-(3+2\tau)\gamma^2]}, \tilde{G}^c = \frac{\gamma^2(3+\tau)^2[\alpha-\beta(C_m+C_r)]^2}{[8\tau\beta-(3+2\tau)\gamma^2]^2}, \tag{27}$$

$$\tilde{T}^c = \frac{\tau(\tau+3)\gamma^2[4\beta(3-\tau)+\tau\gamma^2][\alpha-\beta(C_m+C_r)]^2}{4\beta[8\tau\beta-(3+2\tau)\gamma^2]^2}. \tag{28}$$

4. Comparative analysis

The above contents construct three external R&D situations of the initial state, government subsidies under information symmetry, and government subsidies under information asymmetry, and two internal decision-making situations of decentralized decision-making and centralized decision-making. To facilitate a more intuitive understanding of the differences between the results of the three scenarios and to facilitate subsequent comparative analysis, the results of the three scenarios are summarized in tab. 2 and tab. 3 in this paper.

Table 2. Game equilibrium under decentralized decision-making in different situations

Parameters	Under anarchy	Government subsidies under information symmetry	Government subsidies under information asymmetry
ω	$\frac{4\alpha-\gamma^2+4\beta(C_m-C_r)}{8\beta-\gamma^2}$	$\frac{4\hat{\lambda}^d\alpha-\gamma^2+4\hat{\lambda}^d\beta(C_m-C_r)}{8\hat{\lambda}^d\beta-\gamma^2}$	$\frac{4\widetilde{\lambda}^d\alpha-\gamma^2+4\widetilde{\lambda}^d\beta(C_m-C_r)}{8\widetilde{\lambda}^d\beta-\gamma^2}$
P	$\frac{6\alpha+(2\beta-\gamma^2)(C_m+C_r)}{8\beta-\gamma^2}$	$\frac{6\hat{\lambda}^d\alpha+(2\hat{\lambda}^d\beta-\gamma^2)(C_m+C_r)}{8\hat{\lambda}^d\beta-\gamma^2}$	$\frac{6\widetilde{\lambda}^d\alpha+(2\widetilde{\lambda}^d\beta-\gamma^2)(C_m+C_r)}{8\widetilde{\lambda}^d\beta-\gamma^2}$
Q	$\frac{2\beta[\alpha-\beta(C_m+C_r)]}{8\beta-\gamma^2}$	$\frac{2\hat{\lambda}^d\beta[\alpha-\beta(C_m+C_r)]}{8\hat{\lambda}^d\beta-\gamma^2}$	$\frac{2\widetilde{\lambda}^d\beta[\alpha-\beta(C_m+C_r)]}{8\widetilde{\lambda}^d\beta-\gamma^2}$
G	$\frac{\gamma^2[\alpha-\beta(C_m+C_r)]^2}{(8\beta-\gamma^2)^2}$	$\frac{\gamma^2[\alpha-\beta(C_m+C_r)]^2}{(8\hat{\lambda}^d\beta-\gamma^2)^2}$	$\frac{\gamma^2[\alpha-\beta(C_m+C_r)]^2}{(8\widetilde{\lambda}^d\beta-\gamma^2)^2}$
π_m	$\frac{[\alpha-\beta(C_m+C_r)]^2}{8\beta-\gamma^2}$	$\frac{\hat{\lambda}^d[\alpha-\beta(C_m+C_r)]^2}{8\hat{\lambda}^d\beta-\gamma^2}$	$\frac{\widetilde{\lambda}^d[\alpha-\beta(C_m+C_r)]^2}{8\widetilde{\lambda}^d\beta-\gamma^2}$
π_r	$\frac{4\beta[\alpha-\beta(C_m+C_r)]^2}{(8\beta-\gamma^2)^2}$	$\frac{4\hat{\lambda}^{d2}\beta[\alpha-\beta(C_m+C_r)]^2}{(8\hat{\lambda}^d\beta-\gamma^2)^2}$	$\frac{4\widetilde{\lambda}^{d2}\beta[\alpha-\beta(C_m+C_r)]^2}{(8\widetilde{\lambda}^d\beta-\gamma^2)^2}$
SW	-	$\frac{[14\hat{\lambda}^{d2}\beta-(1-\hat{\lambda}^d\gamma^2)][\alpha-\beta(C_m+C_r)]^2}{(8\hat{\lambda}^d\beta-\gamma^2)^2}$	$\frac{[14\widetilde{\lambda}^{d2}\beta-(1-\widetilde{\lambda}^d\gamma^2)][\alpha-\beta(C_m+C_r)]^2}{(8\widetilde{\lambda}^d\beta-\gamma^2)^2}$

Table 3. Game equilibrium under centralized decision-making in different situations

Parameters	Under anarchy	Government subsidies under information symmetry	Government subsidies under information asymmetry
P	$\frac{2\alpha+(2\beta-\gamma^2)(C_m+C_r)}{4\beta-\gamma^2}$	$\frac{2\hat{\lambda}^c\alpha+(2\hat{\lambda}^c\beta-\gamma^2)(C_m+C_r)}{4\hat{\lambda}^c\beta-\gamma^2}$	$\frac{2\widetilde{\lambda}^c\alpha+(2\widetilde{\lambda}^c\beta-\gamma^2)(C_m+C_r)}{4\widetilde{\lambda}^c\beta-\gamma^2}$
Q	$\frac{2\beta[\alpha-\beta(C_m+C_r)]}{4\beta-\gamma^2}$	$\frac{2\hat{\lambda}^c\beta[\alpha-\beta(C_m+C_r)]}{4\hat{\lambda}^c\beta-\gamma^2}$	$\frac{2\widetilde{\lambda}^c\beta[\alpha-\beta(C_m+C_r)]}{4\widetilde{\lambda}^c\beta-\gamma^2}$
G	$\frac{\gamma^2[\alpha-\beta(C_m+C_r)]^2}{[4\beta-\gamma^2]^2}$	$\frac{\gamma^2[\alpha-\beta(C_m+C_r)]^2}{[4\hat{\lambda}^c\beta-\gamma^2]^2}$	$\frac{\gamma^2[\alpha-\beta(C_m+C_r)]^2}{[4\widetilde{\lambda}^c\beta-\gamma^2]^2}$
π_{sc}	$\frac{[\alpha-\beta(C_m+C_r)]^2}{4\beta-\gamma^2}$	$\frac{\hat{\lambda}^c[\alpha-\beta(C_m+C_r)]^2}{4\hat{\lambda}^c\beta-\gamma^2}$	$\frac{\widetilde{\lambda}^c[\alpha-\beta(C_m+C_r)]^2}{4\widetilde{\lambda}^c\beta-\gamma^2}$
SW	-	$\frac{[6\hat{\lambda}^{c2}\beta-(1-\hat{\lambda}^c)\gamma^2][\alpha-\beta(C_m+C_r)]^2}{(4\hat{\lambda}^c\beta-\gamma^2)^2}$	$\frac{[6\hat{\lambda}^{c2}\beta-(1-\hat{\lambda}^c)\gamma^2][\alpha-\beta(C_m+C_r)]^2}{(4\hat{\lambda}^c\beta-\gamma^2)^2}$

In order to reflect the relationship and difference between these results, our study makes a vertical analysis between three external R&D situations and a horizontal analysis between two decision-making situations. Then we have come to some interesting propositions.

4.1. *Vertical analysis*

Based on the results above mentioned, we initially compare the game equilibria between different external R&D situations. Specifically, our paper discusses the difference in the retail price, market output, and total greenness R&D investment under initial state, government subsidy with information symmetry, and government subsidy with information asymmetry. Thereby, the following propositions can be drawn.

Proposition 3. Whether the manufacturer and retailer make decentralized decisions separately or centralized decisions cooperatively, the government subsidy to the supply chain will lead to increases in the retail price, market output, and green R&D investment. In addition, government subsidy is more effective and the increases in each indicator are more pronounced under information symmetry.

According to **Proposition 3**, we can find that R&D investment increases the green level of products while exacerbating the burdens of enterprises. Green R&D cost is an important expense that supply chain enterprises have to consider. Thereby, government participation in subsidies aims to significantly reduce the pressure on green R&D, which leads to increases in the retail price, product sales, and green R&D investment. Nevertheless, due to the uncertainty of the information environment, the government has no way of knowing whether enterprises are using all of the subsidies in green technology R&D or for other purposes. In reality, government subsidies may be temporarily used to compensate for business problems, which significantly reduces the efficiency of the product's greenness upgrade. This is why, compared to a symmetrical information environment, there is a significant drop in the indicators under information asymmetry.

Proposition 4. When the supply chain members make decentralized decisions, government subsidies for the manufacturer will make the retailer's profit increase more significantly than the manufacturer.

It can be seen that the manufacturer's independent green R&D has obviously positive externalities in decentralized decision-making. That is, the retailer does not participate in green R&D, but the increase in its profits is even more significant. This presents an obvious 'free rider' problem in the economic society. Obviously, as a whole, the improvement in a certain link may improve the efficiency of the overall supply chain, prompting other participants in the supply chain to obtain the non-input output. In addition, due to the uncertainty and risk of technological R&D, this may further suppress manufacturers' enthusiasm for greenness, making this phenomenon more common.

4.2. *Horizontal analysis*

Our study further analyzes game equilibria when the supply chain makes decentralized and centralized decisions. We discuss the retail price, market output, and total greenness R&D investment between decentralized and centralized decision-making. And the following propositions can be drawn.

Proposition 5. Compared with decentralized decision-making, when the manufacturer and retailer make centralized decision-making, it will always be higher output and larger greenness R&D .

Proposition 6. Without government subsidy, the retail price is cheaper when the manufacturer and retailer are in centralized decision-making, while it is uncertain when they are conducting green R&D with government subsidy. Specifically, when $\frac{5}{8} < \frac{\beta}{\gamma^2} < \frac{9+\sqrt{73}}{16}$, $\hat{P}^c > \hat{P}^d$ holds, and when $\frac{\beta}{\gamma^2} \leq \frac{9+\sqrt{73}}{16}$, $\hat{P}^c \leq \hat{P}^d$ holds; when $\frac{5}{8} < \frac{\beta}{\gamma^2} < \frac{11+7\tau+\sqrt{33\tau^2+138\tau+121}}{32\tau}$, $\tilde{P}^c > \tilde{P}^d$ holds, and when $\frac{\beta}{\gamma^2} \geq \frac{11+7\tau+\sqrt{33\tau^2+138\tau+121}}{32\tau}$, $\tilde{P}^c \leq \tilde{P}^d$ holds.

According to **Proposition 5** and **Proposition 6**, we can find that regardless of the external green R&D environment, compared with decentralized decision-making, the output and greenness R&D are larger while the retail price is uncertain in the case of centralized decision-making. When the manufacturer and the retailer opt for decentralized decision-making, this means that the manufacturer will bear the green R&D costs alone, at which point the manufacturer may shift costs through wholesale price and cause the wholesale price to rise obviously. Compared with the manufacturer's independent green R&D investment, the manufacturer and retailer cooperate with each other to jointly undertake the social responsibility of green technology improvement and maximize the benefits of the overall supply chain in the centralized decision-making process, will sharply increase the overall revenue as well as enhance the greenness of the product, which could improve the entire competitiveness of the supply chain. It is an ideal decision-making situation for supply chain members and is conducive to their long-term development. However, the relationship between the magnitudes of the retail price is determined by the values of β and γ. When the value of $\frac{\beta}{\gamma^2}$ is relatively large, the retail price is cheaper under centralized decision-making, and the opposite is true when $\frac{\beta}{\gamma^2}$ is small.

5. Numerical simulation

Due to the complexity of the formulations, only the effects of β and γ on the game equilibrium are discussed in Section 3, in this section, we will further analyze the effects of parameter τ on the equilibrium outcome under information asymmetry. Additionally, we will further comparatively analyze the influence mechanism of different parameters on the game outcomes in different scenarios, also to verify the accuracy of propositions in Section 3 and Section 4. In addition, in the above sections, we mainly consider the influence of parameters on the relatively simple results such as price, output, and greenness in the game equilibrium, but rarely consider the influence of parameters on enterprises' profits and social welfare. In this section, we will further analyze these contents and show the relationships between the parameters and game outcomes with intuitive simulation charts.

In order to simplify the model and facilitate the analysis and research, the corresponding parameters are assigned as follows: $\alpha = 100$, $C_m = 10$, $C_r = 5$, $4 \leq \beta \leq 6$, $1.5 \leq \gamma \leq 2.5$, and $1 \leq \tau \leq 3$. The overall idea of this section is as follows. In Section 5.1, our study will make a comparative analysis through the impacts of parameters β and γ on the equilibrium outcomes under anarchy and government subsidy with information symmetry. We will analyze the differences in equilibrium results between decentralized decision-making and centralized decision-making in these two scenarios mainly by comparing the images from both vertical and horizontal perspectives. In Section 5.2, due to the addition of the parameter τ in the case of information asymmetry, we will further discuss the effects of parameters β, γ, and τ on the game outcomes under government subsidy with information symmetry and government subsidy with information asymmetry. Similar to Section 5.1, we will also analyze the differences between decentralized and centralized decision-making in these two scenarios by employing horizontal and vertical comparisons. The difference is that under government subsidies, social welfare, as an objective function of the government, will be analyzed carefully in this section.

5.1. *Effects of β and γ on game outcomes*

Initially, we analyze the effects of β and γ on P and Q. When discussing the effects of β on the equilibrium outputs, we assign that $4 \leq \beta \leq 6$ and $\gamma = 2$. And when discussing the effects of γ on the equilibrium outputs, we assign that $\beta = 5$ and $1.5 \leq \gamma \leq 2.5$. The relationships between retail price and market output with β and γ under decentralized decision-making and centralized decision-making are shown in fig. 3 and fig. 4.

Obviously, the retail price and market output are decreasing functions with respect to β and increasing functions with respect to γ. Vertically, it is clear that the retail price and market demand both are larger under government subsidy than those under anarchy. This suggests that government subsidies have a significantly positive effect on the supply chain's greenness, which reduces the pressure on the supply chain's R&D and in turn leads to an increase in retail price and market output. Horizontally, we can find that the market demand is always larger under centralized decision-making while the retail price is uncertain. When β is relatively small, the retail price is larger under centralized decision-making. But when γ is relatively small, we will get the opposite conclusion, that is the retail price is larger under decentralized decision-making. It can be seen that the relationship between the retail prices in these two internal decision

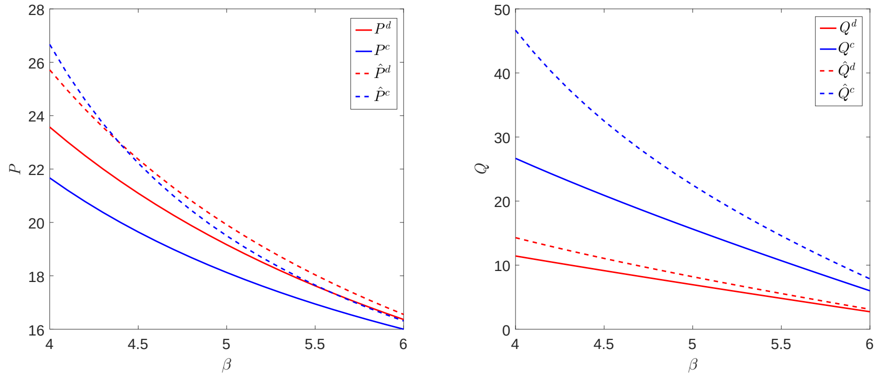


Figure 3. Impacts of β on P and Q

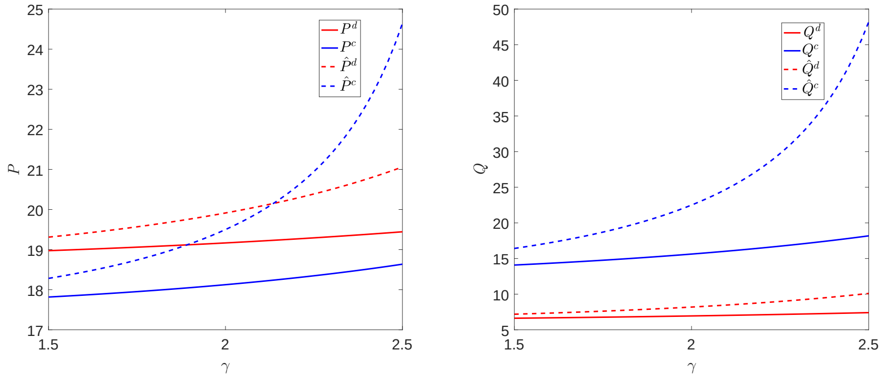


Figure 4. Impacts of γ on P and Q

environments is highly correlated with parameters β and γ.

Moreover, we also discuss the impacts of parameters β and γ on the profits. In particular, we will vertically compare the results between the initial state and government subsidy, and horizontally compare the results under decentralized and centralized decision-making. Similarly, we assign that $\beta = 5$ and $1.5 \leq \gamma \leq 2.5$. The relationships between β and γ and the profits are shown in fig. 5. and fig. 6.

Obviously, we can find that the profits of supply chain participants also increase with the decrease of β and increase with the increase of γ. From a vertical perspective, it can be concluded that the profits of participants are larger with government subsidy whether under decetralized or centralized decision-making. This suggests that government subsidy can clearly increase the profits of all participants, which also means that the effects of government subsidy are remarkable under information symmetry. In addition, the impacts on the profits are more significant when β is small and γ is large, which manifests that green technology investment can make participants more profitable in an environment where consumers have lower price preferences and higher green preferences. Horizontally, by comparing the profits of the manufacturer, retailer, and entire supply chain, we can obtain that the manufacturer's profit is larger than the retailer's under decentralized decision-making while the profits of the entire supply chain are larger in centralized decision-making. Moreover, the gap between the profits of the entire supply chain is larger under government subsidy, which means cooperation in green R&D under government subsidy is a better option for the participants.

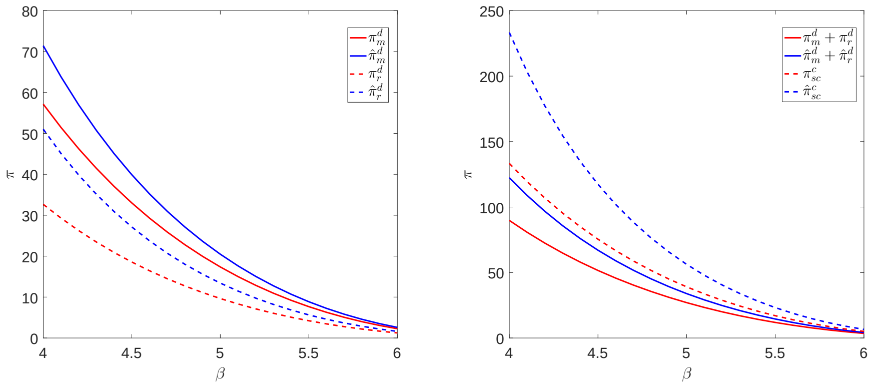


Figure 5. Impacts of β on the profits

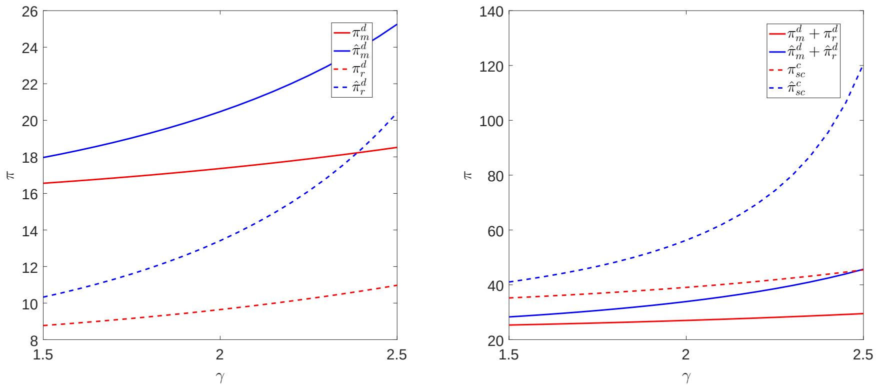


Figure 6. Impacts of γ on the profits

5.2. *Effects of β, γ, and τ on game outcomes*

In this part, we will focus on the effects of parameters β, γ, and τ on the game equilibrium under information asymmetry. Through comparing the results in these two external environments, our study is going to excavate the impact of information asymmetry on participants' game strategy. Similarly, a horizontal and vertical comparative analysis of government subsidies under information symmetry and information asymmetry will be implemented. Since the images of the retail price and market output with respect to β and γ are similar to the results in section 4.1, we will not perform numerical simulations again. In this section, we only pay attention to the relationships between the game equilibria and τ. Detailedly, we will analyze the influence of τ on the retailer price, demand, and participants' profit. Further than the study in the previous section, social welfare and government subsidy investment are included in the discussion, analyzing the impacts through various aspects.

In this section, we analyze the impact of τ on the game equilibrium. We assume that $\beta = 5$, $\gamma = 2$ and $1 \leq \tau \leq 3$, where $\tau = 1$ is the results of governments' subsidies with information symmetry. At this point, the relationships between P, Q, G, T, and τ under information asymmetry are shown in fig. 7.

As is shown in fig. 7, it is clear that an increase in τ will lead to a decrease in these indicators. In other words, from a vertical perspective, P, Q, G and T under the condition of information asymmetry are all smaller than those under the condition

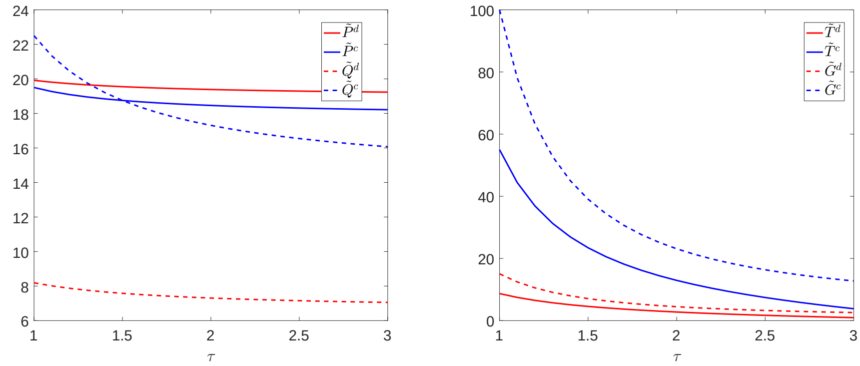


Figure 7. Impacts of τ on P, Q, G and T

of information symmetry. Horizontally, both information symmetry and information asymmetry scenarios result in lower retail prices, higher market demand, and greener products under centralized decision making. Surprisingly, the effects of τ on P and Q are relatively small and only significant on Q under centralized decision-making. On the contrary, its impact on G and T is apparent and the curves decrease rapidly at $1 \leq \tau \leq 2$ and gradually flatten out at $2 < \tau \leq 3$. This may be because when supply chain enterprises misappropriate government subsidies to other places, it leads to a decrease in green R&D, which in turn leads to a decrease in retail price and market output. The government policymakers will reduce subsidy amounts when they observe that the subsidy is ineffective. Thus, in the long run, diverting government subsidies elsewhere is detrimental to the whole supply chain under information asymmetry.

Additionally, our study also discusses the impacts of τ on their profits. Not only do we analyze the relationships between τ and the profits of the supply chain, but we also analyze the relationships between actual revenues and τ under information asymmetry. In this part, we define the profits in products plus unused government subsidy as participants' actual revenues. Likewise, we assume that $\beta = 5$, $\gamma = 2$, and $1 \leq \tau \leq 3$, and the results are shown in fig. 8 and fig. 9.

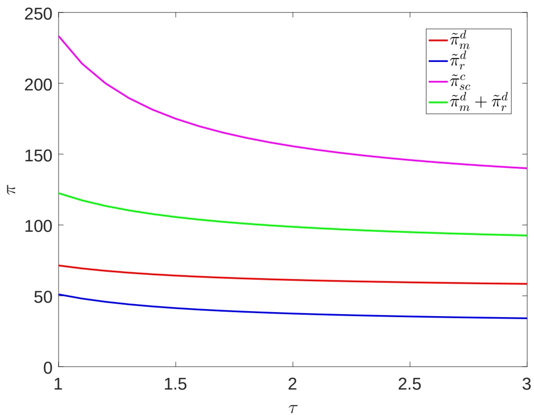


Figure 8. Impacts of τ on the profits

Similarly, since the individual profits of the manufacturer and retailer under decentralized decisions and the overall profits under centralized decisions decrease as τ

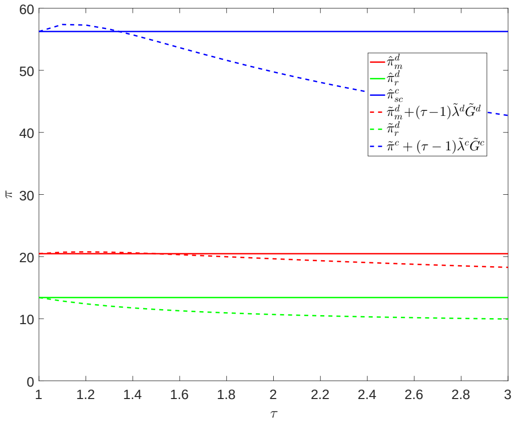


Figure 9. Impacts of τ on actual revenues

increases, this suggests that supply chain firms are more profitable under information symmetry from a vertical perspective, both for centralized decision-making and decentralized decision-making. Specifically, the effect of τ on the profits is more evident under centralized decision-making, and when $1 \leq \tau \leq 2$, an increase in τ will lead to a significant decrease in entire profit, while when $2 < \tau \leq 3$, an increase in τ has little impact on it. This indicates that information asymmetry reduces the greenness of the product, which is detrimental to the supply chain participants and is more pronounced under centralized decision-making. In addition, we can conclude that the supply chain is more profitable under centralized decision making than under decentralized decision making. From fig. 9, we can see that when τ is slightly greater than 1, an increase in τ will lead to an increase in $\tilde{\pi}_{sc}^c$ (i.e., the entire profit is greater than that under information symmetry), while when τ is larger, an increase in τ will lead to a decrease $\tilde{\pi}_{sc}^c$. This is because when τ is small, the proportion of government green subsidy is higher than that under information symmetry. At this point, supply chain participants have lower R&D costs, which in turn will drive up their profits. When τ is relatively large, although the supply chain bears a lower proportion of green R&D, the number of government subsidies will drop significantly, which in turn will lead to a decline in their profits. Obviously, although the misappropriation of government subsidies may solve the problem of participants' internal funding, in the long run, it will inhibit the green development of products and reduce the desire of green consumers to purchase. In fact, when companies divert a large number of subsidy funds, the government will drastically reduce the subsidy, which in turn will lead to a possible return to the pre-subsidy state. Therefore, information asymmetry may also be disadvantageous to the short-term efficiency of the supply chain participants.

Moreover, we will discuss the impact of parameters β and τ on social welfare under information asymmetry. At this point, we assign that $\beta = 5$, $1.5 \leq \gamma \leq 2.5$, $\tau_1 = 1.5$, and $\tau_2 = 2.5$. And then the relationships between γ, τ and social welfare when the manufacturer and retailer make decentralized decision-making and centralized decision-making are shown in fig. 10.

As is shown in fig. 10, it is evident to see that social welfare is higher under collaborative R&D. Centralized decision-making on green R&D by the manufacturer and retailer is not only beneficial to the overall profitability of both, but also to the entire welfare of society. Furthermore, we find that social welfare increases with γ and

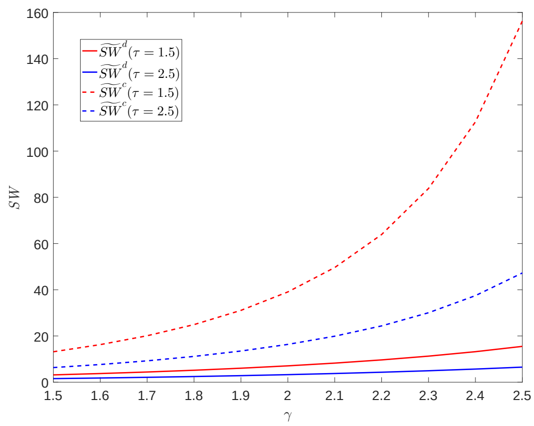


Figure 10. Impacts of β and τ on social welfare

decreases with τ, and that γ has a smaller effect on it. Understandably, in an environment where consumers prefer green products, government subsidies can help increase the greenness of products, which in turn can increase the profitability of supply chain enterprises and increase the purchasing utility of consumers. However, due to the information asymmetry between enterprises and the government, supply chain enterprises may not fully utilize government subsidies, which leads to a significant reduction in green R&D investment and thus in turn will reduce the greenness of products as well as the utility for consumers. Information asymmetry is also one of the major reasons why government subsidies do not achieve the desired results, and this is precisely why China's subsidy policy for green-car has been ineffective.

6. Conclusions and management insights

6.1. *Conclusions*

Our study considers three external environments in green R&D which are initial state, government subsidy under information symmetry and information asymmetry, and two internal environments in the decision which are centralized and decentralized decision-making. Through comparing the game equilibria in different scenarios, we can draw the following conclusions.

In general, the retail price, market output, R&D investment, and participants' profits are decreasing functions of the price parameter β and information environment parameter τ, and increasing functions of the green preference parameter γ, which suggests that increased consumer preference is beneficial to supply chain enterprises, while increased price preference and information asymmetry have a negative effect on their strategies. Longitudinally, government subsidies for the supply chain's green R&D investment will lead to a higher price for the final product, larger output in the market, and higher profits for supply chain enterprises in the game equilibrium. However, due to the information asymmetry between the government and the supply chain, this may lead to some reduction in the effectiveness of government subsidies. Horizontally, we can see that regardless of the external environments, market output and green R&D are always greater under centralized decision-making. Differently, although the retail price is also lower under centralized decision-making in the initial state, with the support of government subsidy, it is higher under centralized decision-making when $\frac{\beta}{\gamma^2}$ is relatively small.

Government subsidy can significantly increase the total R&D expenditures of the supply chain, which effectively improves the greenness of the product. And it is evident that the government subsidy ratio to the supply chain is higher under decentralized decision-making while the subsidy investment is larger under centralized decision-making. Additionally, when the manufacturer and retailer make the decentralized decision since the retailer does not participate in green R&D, it becomes a free rider and its profits rise more sharply than the manufacturer. This suggests that there is a clear positive externality when the core enterprise undertakes R&D costs alone as its success in green technology will inevitably benefit other enterprises in the supply chain. To sum up, centralized decision-making is a better choice for the manufacturer and retailer and is more conducive to enhancing the greenness of the products.

Nevertheless, due to information asymmetry, the amount of the government subsidy may not be fully utilized in green R&D, which reduces the efficiency of government subsidy. Low utilization of government subsidies will significantly reduce the amount actually spent on green R&D, which in turn will lead to a decrease in price and production. When τ is small, the incomplete utilization of subsidy will indeed increase the actual revenues of supply chain participants, however, when τ is large, government subsidy will also decline significantly and then the funds available for green R&D will shrink significantly, which is also disadvantageous for the supply chain participants. Information asymmetry does not necessarily benefit supply chain firms either. Furthermore, an increase in τ will lead to a decrease in social welfare while an increase in γ will lead to an increase in social welfare, and the effect of γ on social welfare is greater, indicating that social welfare is more influenced by consumers' preference for product greenness.

6.2. *Management insights*

Based on the above findings, we provide some recommendations for decision-makers in government and the supply chain.

(1) Supply chain enterprises should seek to exchange information and share the social responsibility of green technology R&D, which not only helps to reduce the risk and financial pressure of individual R&D but is also beneficial to improving the profitability of the whole supply chain. Collaborative R&D between the manufacturer and retailer can spread the risk of R&D and increase total investment in R&D. This can be more effective in promoting the green upgrade of products, which is beneficial for both parties. For example, the manufacturers and retailers can sign contracts to reduce the wholesale price, and accordingly, the retailer needs to bear part of the expenditure of R&D.

(2) Enterprise managers need to pay more attention to the green demands of consumers since their demands for product greenness plays a crucial role in enterprises' strategic decisions. When consumers' green preference for products is relatively low, the increase in profits is limited after green R&D, but when consumers' green preference is quite large, green R&D will become important competitiveness for companies. In addition, the reason for the low consumer demand for products may be that the products have not yet reached the consumer's green expectations. Therefore, companies should further analyze the level of consumer demand for green products before making green R&D decisions, which is a more sound strategy for managers.

(3) The government should improve the subsidy mechanism to prevent supply chain enterprises from exploiting the loopholes of the subsidy policy. The government should urge enterprises to disclose the use of their subsidy funds to ensure that the funds can be used for product green R&D as much as possible. Furthermore, the government can reduce the number of subsidized enterprises to increase the competitiveness of the market, which can mobilize enthusiasm and can promote the green level of products in the whole market under the elimination of winners and losers.

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Appendices

1. Proof of equations

Proof of equations (11), (12) and (13)

Similar to the proof process of equations (3) and (4), we can obtain that $|H| = \frac{\gamma}{16\hat{G^d}^{\frac{3}{2}}}[\frac{2\beta(\hat{\omega}^d - C_m)}{\gamma} - \hat{G^d}^{\frac{1}{2}}] \geq 0$ holds. The Hessian matrix is negative definite and there is a maximum value with respect to $\hat{\omega}^d$ and $\hat{G}^d$. Thus, we let $\frac{\partial \hat{\pi}_m^d}{\partial \hat{G}^d} = 0$ and $\frac{\partial \hat{\pi}_m^d}{\partial \hat{\omega}^d} = 0$, and then obtain $\hat{\omega}^d = \frac{4\hat{\lambda}^d\alpha - \gamma^2 C_m + 4\hat{\lambda}^d\beta(C_m - C_r)}{8\hat{\lambda}^d\beta - \gamma^2}$ and $\sqrt{\hat{G}^d} = \frac{\gamma[\alpha - \beta(C_m + C_r)]}{8\hat{\lambda}^d\beta - \gamma^2}$, where $\hat{\lambda}^d = \frac{4}{9} - \frac{\gamma^2}{36\beta}$. Substituting them into equation (8) and making $\frac{\partial \widehat{SW^d}}{\partial \hat{\lambda}^d} = 0$, then we can get $\hat{\lambda}^d = \frac{4}{9} - \frac{\gamma^2}{36\beta}$. Therefore, we can obtain the results of equations (11), (12) and (13).

Proof of equations (16) and (17)

Similar to the proof process of equation (6), we can obtain that $|H| = \frac{\gamma[2\beta(\hat{P}^c - C_m - C_r) - \gamma\sqrt{\hat{G}^c}]}{4\hat{G^c}^{\frac{3}{2}}} \geq 0$ holds. Thereby, the Hessian matrix is negative definite and there is a maximum value with respect to $\hat{P}_c$ and $\hat{G}_c$. We let $\frac{\partial \hat{\pi}_{sc}^c}{\partial \hat{P}^c} = 0$, $\frac{\partial \hat{\pi}_{sc}^c}{\partial \hat{G}^c} = 0$ and obtain $\hat{P}^c = \frac{2\hat{\lambda}^c\alpha + (2\hat{\lambda}^c\beta - \gamma^2)(C_m + C_r)}{4\hat{\lambda}^d\beta - \gamma^2}$ and $\sqrt{\hat{G}^c} = \frac{\gamma[\alpha - \beta(C_m + C_r)]}{4\hat{\lambda}^c\beta - \gamma^2}$. Substituting them into equation (14) and making $\frac{\partial \widehat{SW^c}}{\partial \hat{\lambda}^c} = 0$, then we can get $\hat{\lambda}^c = \frac{1}{2} - \frac{\gamma^2}{16\beta}$. Therefore, we can obtain the results of equations (16) and (17).

Proof of equations (21), (22) and (23); (26), (27) and (28)

The proof processes of equations (21), (22) and (23) are similar to those of equations (11), (12) and (13), and the proof processes of equations (26), (27) and (28) are also similar to those of equations (16), and (17), so we do not repeat them.

2. Proof of propositions

Proof of proposition 1

When the manufacturer and retailer decentralize decision-making, we separately calculate the partial derivatives of P^d, Q^d, and G^d with respect to β and γ. Since $8\beta - \gamma^2 > 0$ and $\alpha - \beta(C_m + C_r) > \alpha - \beta P > 0$, thus we can obtain that $\frac{\partial P^d}{\partial \beta} = \frac{6[\gamma^2(C_m + C_r) - 8\alpha]}{(8\beta - \gamma^2)^2} < \frac{6[8\beta(C_m + C_r) - 8\alpha]}{(8\beta - \gamma^2)^2} < 0$, $\frac{\partial Q^d}{\partial \beta} = \frac{2\gamma^2[\beta(C_m + C_r) - \alpha] + 2\beta(C_m + C_r)(\gamma^2 - 8\beta)}{(8\beta - \gamma^2)^2} < 0$, and $\frac{\partial G^d}{\partial \beta} = -\frac{2[\alpha - \beta(C_m + C_r)][8\alpha - \gamma^2(C_m + C_r)]}{(8\beta - \gamma^2)^3} < 0$; and $\frac{\partial P^d}{\partial \gamma} = \frac{12\gamma[\alpha - \beta(C_m + C_r)]}{(8\beta - \gamma^2)^2} > 0$, $\frac{\partial Q^d}{\partial \gamma} = \frac{4\beta\gamma[\alpha - \beta(C_m + C_r)]}{(8\beta - \gamma^2)^2} > 0$, and $\frac{\partial G^d}{\partial \gamma} = \frac{4\gamma[\alpha - \beta(C_m + C_r)]^2}{(8\beta - \gamma^2)^3} > 0$. Similarly, when the manufacturer and retailer centralize decision-making, we separately calculate the partial derivatives of P^c, Q^c, and G^c with respect to β and γ. Since $4\beta - \gamma^2 > 0$ and $\alpha - \beta(C_m + C_r) > \alpha - \beta P > 0$, we can obtain that $\frac{\partial P^c}{\partial \beta} = \frac{2\gamma^2(C_m + C_r) - 8\alpha}{(4\beta - \gamma^2)^2} < \frac{8\beta(C_m + C_r) - 8\alpha}{(4\beta - \gamma^2)^2} < 0$, $\frac{\partial Q^c}{\partial \beta} = \frac{2\gamma^2[\beta(C_m + C_r) - \alpha] + 2\beta(C_m + C_r)(\gamma^2 - 4\beta)}{(4\beta - \gamma^2)^2} < 0$, $\frac{\partial G^c}{\partial \beta} = -\frac{2[\alpha - \beta(C_m + C_r)][4\alpha - \gamma^2(C_m + C_r)]}{(4\beta - \gamma^2)^3} < 0$; and $\frac{\partial P^c}{\partial \gamma} = \frac{4\gamma^2[\alpha - \beta(C_m + C_r)]}{(4\beta - \gamma^2)^2} > 0$, $\frac{\partial Q^c}{\partial \gamma} = \frac{4\beta\gamma[\alpha - \beta(C_m + C_r)]}{(4\beta - \gamma^2)^2} > 0$, and $\frac{\partial G^c}{\partial \beta} = \frac{4\gamma[\alpha - \beta(C_m + C_r)]^2}{(4\beta - \gamma^2)^3} > 0$. Therefore, we can obtain the conclusion as **proposition 1**.

Proof of proposition 2

When the manufacturer and the retailer make decentralized decision, and due to $32\beta - 11\gamma^2 > 0$ and $\alpha - \beta(C_m + C_r) > 0$, we can obtain that $\frac{\partial \tilde{P}^d}{\partial \beta} = \frac{432\beta^2(C_m + C_r) - 1536\alpha\beta^2 + 3\alpha(64\beta^2 - 11\gamma^2)}{2\beta^2(32\beta - 11\gamma^2)}$, $\frac{\partial \tilde{Q}^d}{\partial \beta} = -\frac{512\beta^2(C_m + C_r) + 144\alpha\gamma^2 - 352\beta\gamma^2(C_m + C_r) + 11\gamma^4(C_m + C_r)}{2(32\beta - 11\gamma^2)}$, and $\frac{\partial \tilde{G}^d}{\partial \beta} = -\frac{162[\alpha - \beta(C_m + C_r)][32\alpha - 11\gamma^2(C_m + C_r)]}{(32\beta - 11\gamma^2)^3} < 0$; $\frac{\partial \tilde{P}^d}{\partial \gamma} = \frac{432\gamma[\alpha - \beta(C_m + C_r)]}{(32\beta - 11\gamma^2)^2} > 0$,

$\frac{\partial \tilde{Q}^d}{\partial \gamma} = \frac{144\gamma[\alpha-\beta(C_m+C_r)]}{(32\beta-11\gamma^2)^2} > 0$, and $\frac{\partial \tilde{G}^d}{\partial \gamma} = \frac{162\gamma[\alpha-\beta(C_m+C_r)]^2(32\beta+11\gamma^2)}{(32\beta-11\gamma^2)^2} > 0$. Further, we assume that $F_1(\beta) = 432\beta^2(C_m + C_r) - 1536\alpha\beta^2 + 3\alpha(64\beta^2 - 11\gamma^2)$ and $F_2(\beta) = 512\beta^2(C_m + C_r) + 144\alpha\gamma^2 - 352\beta\gamma^2(C_m + C_r) + 11\gamma^4(C_m + C_r)$. Since $\Delta_1 = -5184[32\alpha - 11\gamma^2(C_m + C_r)] < 0$ and $432\gamma^2(C_m + C_r) - 1526\alpha < 0$, $\Delta_2 = -9216\gamma^2(C_m + C_r)[32\alpha - 11\gamma^2(C_m + C_r)] < 0$ and $-512 < 0$, we can obtain that $\frac{\partial \tilde{P}^d}{\partial \beta} < 0$, $\frac{\partial \tilde{Q}^d}{\partial \beta} < 0$. Similarly, when the manufacturer and the retailer make decentralized decision, and due to $8\beta - 5\gamma^2 > 0$ and $\alpha - \beta(C_m + C_r) > 0$, we can obtain that $\frac{\partial \tilde{P}^c}{\partial \beta} = \frac{32\beta^2\gamma^2(C_m+C_r)+\alpha(-64\beta^2+16\beta\gamma^2-5\gamma^4)}{2\beta^2(8\beta-5\gamma^2)^2}$, $\frac{\partial \tilde{Q}^c}{\partial \beta} = -\frac{64\beta^2(C_m+C_r)+32\alpha\gamma^2-80\beta\gamma^2(C_m+C_r)+5\gamma^4(C_m+C_r)}{2(8\beta-5\gamma^2)^2}$, and $\frac{\partial \tilde{G}^c}{\partial \beta} = -\frac{32[\alpha-\beta(C_m+C_r)][8\alpha-5\gamma^2(C_m+C_r)]}{(8\beta-5\gamma^2)^3} < 0$; $\frac{\partial \tilde{P}^c}{\partial \gamma} = \frac{32\gamma[\alpha-\beta(C_m+C_r)]}{(8\beta-5\gamma^2)^2} > 0$, $\frac{\partial \tilde{Q}^c}{\partial \gamma} = \frac{32\beta\gamma[\alpha-\beta(C_m+C_r)]}{(8\beta-5\gamma^2)^2} > 0$, and $\frac{\partial \tilde{G}^c}{\partial \gamma} = \frac{32\gamma[\alpha-\beta(C_m+C_r)](8\beta+5\gamma^2)}{(8\beta-5\gamma^2)^3} > 0$. Also, we assume that $F_3(\beta) = 32\beta^2\gamma^2(C_m + C_r) + \alpha(-64\beta^2 + 16\beta\gamma^2 - 5\gamma^4)$ and $F_4(\beta) = 64\beta^2(C_m + C_r) + 32\alpha\gamma^2 - 80\beta\gamma^2(C_m + C_r) + 5\gamma^4(C_m + C_r)$. Since $\Delta_3 = -138[8\alpha - 5\gamma^2(C_m + C_r)] < 0$ and $32\gamma^2(C_m + C_r) - 64\alpha < 0$, $\Delta_2 = -1024\gamma^2(C_m + C_r)[8\alpha - 5\gamma^2(C_m + C_r)] < 0$ and $-64 < 0$, we can obtain $\frac{\partial \tilde{P}^c}{\partial \beta} < 0$ and $\frac{\partial \tilde{Q}^c}{\partial \beta} < 0$.

Proof of proposition 3

When the manufacturer and retailer choose decentralized decision-making, we comparatively analyze the results when the game is in equilibrium in different statuses. First, we compared the game equilibria between the results under three scenarios. We can get that $\tilde{P}^d - P^d = \frac{6(1-\tilde{\lambda}^d)\gamma^2[\alpha-\beta(C_m+C_r)]}{(8\beta-\gamma^2)(8\tilde{\lambda}^d\beta-\gamma^2)}$, $\tilde{Q}^d - Q^d = \frac{2(1-\tilde{\lambda}^d)\beta\gamma^2[\alpha-\beta(C_m+C_r)]}{(8\beta-\gamma^2)(8\tilde{\lambda}^d\beta-\gamma^2)}$, and $\tilde{G}^d - G^d = \frac{[(8\beta-\gamma^2)^2-(8\tilde{\lambda}^d\beta-\gamma^2)^2]\gamma^2[\alpha-\beta(C_m+C_r)]^2}{(8\beta-\gamma^2)^2(8\tilde{\lambda}^d\beta-\gamma^2)^2}$. Since $\tilde{\lambda}^d = \frac{\tau(16\beta-\gamma^2)}{28\beta+8\beta\tau}$, we can get $1 - \tilde{\lambda}^d > 0$, $\tau > 1$ and $8\tilde{\lambda}^d\beta - \gamma^2 = \frac{32\beta-(4+\frac{7}{\tau})}{\frac{7}{\tau}+2} > 0$. Thus, we can obtain $\tilde{P}^d - P^d > 0$, $\tilde{Q}^d - Q^d > 0$, and $\tilde{G}^d - G^d > 0$. Further, we can obtain that $\hat{P}^d - \tilde{P}^d = \frac{6(\tilde{\lambda}^d-\hat{\lambda}^d)\gamma^2[\alpha-\beta(C_m+C_r)]}{(8\hat{\lambda}^d\beta-\gamma^2)(8\tilde{\lambda}^d\beta-\gamma^2)}$, $\hat{Q}^d - \tilde{Q}^d = \frac{2(\tilde{\lambda}^d-\hat{\lambda}^d)\beta\gamma^2[\alpha-\beta(C_m+C_r)]}{(8\hat{\lambda}^d\beta-\gamma^2)(8\tilde{\lambda}^d\beta-\gamma^2)}$, and $\hat{G}^d - \tilde{G}^d = \frac{[(8\tilde{\lambda}^d\beta-\gamma^2)^2-(8\hat{\lambda}^d\beta-\gamma^2)^2]\gamma^2[\alpha-\beta(C_m+C_r)]^2}{(8\hat{\lambda}^d\beta-\gamma^2)^2(8\tilde{\lambda}^d\beta-\gamma^2)^2}$. Since $\hat{\lambda}^d = \frac{4}{9} - \frac{\gamma^2}{36\beta}$, we can get $\tilde{\lambda}^d - \hat{\lambda}^d = \frac{7(16\beta-\gamma^2)(\tau-1)}{36\beta(7+2\tau)} > 0$, $8\hat{\lambda}^d\beta - \gamma^2 = \frac{32\beta-11\gamma^2}{11} > 0$, and $8\tilde{\lambda}^d\beta - \gamma^2 > 0$. Thereby, we can obtain $\hat{P}^d - \tilde{P}^d > 0$, $\hat{Q}^d - \tilde{Q}^d > 0$, and $\hat{G}^d - \tilde{G}^d > 0$. Putting the above analysis together, we can see that $\hat{P}^d > \tilde{P}^d > P^d$, $\hat{Q}^d > \tilde{Q}^d > Q^d$, and $\hat{G}^d > \tilde{G}^d > G^d$. Similar to the above proof process, comparing the results of the game equilibra under centralized decision-making, we obtain that $\hat{P}^c > \tilde{P}^c > P^c$, $\hat{Q}^c > \tilde{Q}^c > Q^c$, and $\hat{G}^c > \tilde{G}^c > G^c$.

Proof of proposition 4

In a decentralized decision-making supply chain, when the government subsidizes manufacturers' green R&D, we express the change in profit under information symmetry and information asymmetry as a ratio, resulting in $\frac{\hat{\pi}_m^d}{\pi_m^d} = \frac{\hat{\lambda}^d(8\beta-\gamma^2)}{8\hat{\lambda}^d\beta-\gamma^2}$, $\frac{\hat{\pi}_r^d}{\pi_r^d} = [\frac{\hat{\lambda}^d(8\beta-\gamma^2)}{8\hat{\lambda}^d\beta-\gamma^2}]^2$, $\frac{\tilde{\pi}_m^d}{\pi_m^d} = \frac{\tilde{\lambda}^d(8\beta-\gamma^2)}{8\tilde{\lambda}^d\beta-\gamma^2}$, and $\frac{\tilde{\pi}_r^d}{\pi_r^d} = [\frac{\tilde{\lambda}^d(8\beta-\gamma^2)}{8\tilde{\lambda}^d\beta-\gamma^2}]^2$. Since $\hat{\lambda}^d(8\beta-\gamma^2) > 8\hat{\lambda}^d\beta-\gamma^2 > 0$, we can see that $\frac{\hat{\lambda}^d(8\beta-\gamma^2)}{8\hat{\lambda}^d\beta-\gamma^2} > 1$, then we can get $\frac{\hat{\pi}_r^d}{\pi_r^d} > \frac{\hat{\pi}_m^d}{\pi_m^d}$. Also, we can obtain $\frac{\tilde{\pi}_r^d}{\pi_r^d} > \frac{\tilde{\pi}_m^d}{\pi_m^d}$.

Proof of proposition 5

When the supply chain invests in greenness R&D under anarchy, we obtain the result that $Q^c - Q^d = \frac{8\beta^2[\alpha-\beta(C_m+C_r)]}{(8\beta-\gamma^2)(4\beta-\gamma^2)} > 0$ and $\sqrt{G^c} - \sqrt{G^d} = \frac{4\beta\gamma[\alpha-\beta(C_m+C_r)]}{(8\beta-\gamma^2)(4\beta-\gamma^2)} > 0$. Thus, we can obtain that $Q^c > Q^d$ and $G^c > G^d$. Similarly, in the case of government subsidy under information symmetry, we can obtain that $\hat{Q}^c - \hat{Q}^d = \frac{[\alpha-\beta(C_m+C_r)][64(\frac{\beta}{\gamma^2})^2-16\frac{\beta}{\gamma^2}+3]}{(8\beta-5\gamma^2)(32\beta-11\gamma^2)}$ and $\sqrt{\hat{G}^c} - \sqrt{\hat{G}^d} = \frac{\gamma(56\beta+\gamma^2)[\alpha-\beta(C_m+C_r)]}{(8\beta-5\gamma^2)(32\beta-11\gamma^2)}$. Since $8\beta > 5\gamma^2$ and $\Delta = -512 < 0$, we can obtain that $\hat{Q}^c > \hat{Q}^d$ and $\hat{G}^c > \hat{G}^d$. And when in the case of government subsidy under information asymmetry, we can obtain that $\tilde{Q}^c - \tilde{Q}^d = \frac{\tau[\alpha-\beta(C_m+C_r)][64\tau(\frac{\beta}{\gamma^2})^2-4(1+3\tau)\frac{\beta}{\gamma^2}+(2+\tau)]}{[8\beta\tau-\gamma^2(3+2\tau)][32\tau\beta-\gamma^2(7+4\tau)]}$ and $\sqrt{\tilde{G}^c} - \sqrt{\tilde{G}^d} = \frac{\tau\gamma(8\beta(5+2\tau)+\gamma^2)[\alpha-\beta(C_m+C_r)]}{[8\beta\tau-\gamma^2(3+2\tau)][32\tau\beta-\gamma^2(7+4\tau)]}$. Since $\tau > 1$, then $8\beta - \gamma^2(\frac{3}{\tau} + 2) > 0$ and $32\beta - \gamma^2(\frac{7}{\tau} + 4) > 0$, thus $\tilde{Q}^c > \tilde{Q}^d$ holds. Additionally, since $\Delta = 16(1 - 26\tau - 7\tau^2) < 0$, we can obtain $\tilde{G}^c > \tilde{G}^d$.

Proof of proposition 6

When the manufacturer and retailer conduct green R&D under anarchy, we can obtain the result that $P^c - P^d = \frac{4(\gamma^2-2\beta)[\alpha-\beta(C_m+C_r)]}{(8\beta-\gamma^2)(4\beta-\gamma^2)} < 0$. Under government subsidy, when the supply chain and the government are information symmetry, we can get that $\hat{P}^c - \hat{P}^d = -\frac{2[\alpha-\beta(C_m+C_r)][32(\frac{\beta}{\gamma^2})^2-36\frac{\beta}{\gamma^2}+1]}{(8\beta-5\gamma^2)(32\beta-11\gamma^2)}$. Since $\frac{\beta}{\gamma^2} > \frac{5}{8}$, we can obtain that $\hat{P}^c > \hat{P}^d$ holds when $\frac{5}{8} < \frac{\beta}{\gamma^2} < \frac{9+\sqrt{73}}{16}$, and the opposite is true when $\frac{\beta}{\gamma^2} \geq \frac{9+\sqrt{73}}{16}$. Similarly, when the supply chain and the government is information asymmetry, we can obtain that $\tilde{P}^c > \tilde{P}^d$ holds when $\frac{5}{8} < \frac{\beta}{\gamma^2} < \frac{11+7\tau+\sqrt{121+138\tau+33\tau^2}}{32\tau}$, and the opposite is true when $\frac{\beta}{\gamma^2} \geq \frac{11+7\tau+\sqrt{121+138\tau+33\tau^2}}{32\tau}$.