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Green degree decision and pricing strategy of dual-channel supply chains

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With the prevalence of green supply chains, the government has basic requirements for companies' green investments and outcomes while consumers increasingly favor green products. Thus, green degree decision has garnered significant attention from manufacturers. This paper incorporates green degree decisions into a dual-channel supply chain and adopts a Stackelberg model to analyze the green degree and pricing strategies under centralized and decentralized decisions. We find that, when the manufacturer only decides on price, dual-channel choice is always the optimal strategy under centralized decision-making; however, under decentralized decision-making, the dual-channel choice will be chosen only when the wholesale price is low. Considering green degree decision, both direct and indirect channel prices increase with the green degree, and the indirect channel price is more sensitive to changes in the green degree under centralized decision-making; and higher green degrees are always advantageous for the retailer, but the manufacturer's profit initially decreases and then increases as the green degree rises under decentralized decision-making. Moreover, the wholesale price is used as a strategic tool for the manufacturer to control the distribution channel, particularly when the green degree is not introduced, the manufacturer can always ensure the introduction of dual channels. Besides, higher consumers' environmental awareness is always beneficial to channel members, as it promotes channel prices and green degree. This study provides strategic insights for optimizing pricing and green degree decisions in dual-channel supply chains to achieve better economic and environmental outcomes.

KEYWORDS

dual channel, green degree, pricing strategy, green product, stackelberg game

1 Introduction

Environmental issues have long been one of the most important and widely discussed topics around the world, especially in recent years as we suffered from increasing environmental crises. The international community has reached a certain consensus on promoting green trade. In 2021, the United Nations Environment Programme released "Green International Trade: Pathways Forward," which extensively discusses green trade and proposes building an Agenda 2.0 for environment and trade. This includes strengthening trade-related environmental policies, promoting upgraded environmental regulations in trade policies and agreements, and advancing cooperation between environment and trade. Green trade encompasses measures for green trade practices and the trade of green products. Some sustainable development concepts, including low-carbon economy and green GDP, have been widely accepted, and thereby promoting research into green products.

Environmental concerns have compelled manufacturers and retailers to rethink various aspects such as inventory decisions, product innovation, returns management, reverse logistics design, and coordination among channel participants. For instance, Pepsi, a large-scale manufacturer, uses reusable transport containers instead of corrugated materials for shipping to protect the environment[1]. Adidas, a globally renowned sports goods manufacturer, has greened its products from sourcing raw materials to manufacturing and packaging to reduce environmental impact[2]. Retailing giant Walmart is dedicated to retailing green products. One of the three major corporate goals set by Walmart's CEO in October 2005 is to sell green products that balance corporate resources with environmental protection[3]. Apart from Walmart, another major retailer, Best Buy, sells appliances certified by "Energy Star," which enhances competitiveness and significantly contributes to environmental protection[4].

For today's manufacturers, the green degree decision of products has been a key focus. On the one hand, manufacturers have to reach the green standards required by the government; on the other hand, more and more consumers also prefer green products to regular ones. Generally speaking, the green degree refers to the environmental protection level of a green product throughout its lifecycle. Sometimes, it also represents a comprehensive indicator of the technical, economic, and environmental harmony of green products. Products with higher green degrees usually attract more consumers with environmental concerns but tend to cost manufacturers more to produce them. Research on green degree mainly focuses on two areas: constructing evaluation indicators for green degree, using methods such as grey system decision-making, weighted scoring, Topsis method, expert consultation, etc.; and regarding the green degree as a decision variable to incentivize and coordinate green supply chains.

Nowadays, most products are sold through multi-channels or dual channels. A dual-channel refers to a channel structure combining direct and indirect channels (Beck and Rygl, 2015). With the emergence of the Internet, dual-channel become common practices for manufacturers. For example, Pepsi and Adidas sell their products through both retail partners and their websites. Retail giants such as Wal-Mart and Amazon also expanded their channels that Wal-Mart introduced its online channel Walmart. Com in 2000, while Amazon launched an offline strategy by opening a physical bookstore in 2015. This trend further promotes the manufacturers' adoption of dual-channel.

This paper incorporates green product decisions into the dual-channel supply chain. Based on the Stackelberg game model, we analyze manufacturers' green degree and pricing strategies with decentralized and centralized decisions to provide optimal pricing and green degree references for green product manufacturers. This paper aims to address the following questions: (1) When the manufacturer jointly decides on pricing and green degree, how do the manufacturer and retailer coordinate their decision to maximize their profits? (2) How does the green degree affect the indirect channel price and direct channel price? (3) How does the manufacturer influence a retailer by controlling the wholesale price in a dual-channel framework? (4) How external factors such as potential channel market share and consumers' environmental awareness in different channels influence the optimal decision-making of manufacturer and retailer?

2 Literature review

Our study is closely related to three research streams: green product, dual-channel, and green supply chain management.

Existing literature regarding green products has examined green products with and without the consideration of recyclability, the measurement of green transition, the optimization of green degree, and so on (Ghosh and Shah, 2012; Sheu and Chen, 2012; Zhai et al., 2022; Guo et al., 2020). Recently, Dong et al. (2021) analyze the coupling coordination relationship between green urbanization and green finance using the data in China during 2010–2017.

From a corporate perspective, the price of green products may be higher, and consumers are willing to pay a premium for higher environmental performance (Dangelico and Vocalelli, 2017). Dangelico and Vocalelli (2017) pointed out that positioning green features as one of many product attributes is more advantageous than solely targeting green products. Companies should also establish and market a unique green brand image, as consumers are more likely to purchase green products when they are more familiar with green brands (Mohd Suki, 2016). Furthermore, successful green brand positioning can differentiate products and create additional demand (Mohd Suki, 2016). Through studying the quality and satisfaction of guests' experiences at green hotels, Wu et al. (2016) find that a hotel's green image can enhance customers' trust and satisfaction with the green hotel, thereby reducing their intention to switch. Additionally, companies that implement green process innovation and green product innovation can improve their financial performance by enhancing resource utilization efficiency, reducing costs, and increasing market competitiveness (Xie et al., 2019). Green et al. (2012) find that a company's green supply chain management (GSCM) positively impacts both environmental and economic performance, as well as operational and organizational performance.

A concept related to green products is green innovation, which is a broad concept often intertwined with sustainable development, aiming to balance economic growth with sustainability. Kemp and Arundel (1998) introduce a widely accepted definition of green innovation, defining it as the development of new systems, technologies, and products aimed at reducing environmental damage. This definition transcends mere product innovation, encompassing systemic innovation within organizations. Driessen

1 http://www.pepsico.com.cn/purpose/Sustainable-Food-System-Key.html

2 https://www.adidas.com/us/go/campaign/sustainability/reduce-footprint

3 http://www.wal-martchina.com/community/community.htm

4 https://corporate.bestbuy.com/energy-star-partner-of-the-year-2024/

et al. (2013) provide a pragmatic definition of green innovation, emphasizing its goal of generating significant environmental benefits rather than merely reducing environmental harm. Karakaya et al. (2014) conduct a literature review on green innovation using the Google Scholar database from 1990 to 2012. They find over a thousand highly cited publications, with a notable increase in high-quality green innovation research starting around 2006, peaking significantly by 2008. Zhao et al. (2022) explore the relationship between the academic experience of executives and green innovation and find that the academic experience of senior managers significantly affects firms' green innovation in emerging markets. Moreover, governments are also promoting corporate green innovation. Government-promoted carbon emission trading pilot policies have significantly facilitated intercity green innovation cooperation and elevated the level of regulated firms' green innovation (Yu et al., 2022; Xiaobao et al., 2024). Mazzarano (2024) find that decarbonization policies can help companies reduce costs, improve efficiency, enhance brand image, increase market value, and achieve sustainable development, while also bringing more positive externalities to society. These decarbonization policies are driven both by government initiatives and by companies' strategic development choices (Mazzarano, 2024).

Research on dual-channel has long been a popular topic since it offers opportunities to serve different segmented customers, create synergies, and develop economies of scale. However, Agatz et al. (2008) point out that, to successfully implement dual-channel distribution, dual-channel distribution systems require a continuous balance between integration and separation across the two channels. Considering consumer preferences, Hua et al. (2010) analyze the impact of customer acceptance and delivery times on pricing strategies for decision-makers. Melis et al. (2015) find that when consumers try online shopping, they tend to choose the online stores of the same chain as their offline stores, especially when the product varieties are highly integrated between the dual channels. Considering retail risk preference in dual channels, Jiang et al. (2017) analyze the effects on channel strategies based on retail risk aversion or risk preference. Some recent research about dual channels incorporates consumer service, agency selling, store brand introduction, and so on into consideration to generate new insights for dual channel literature (Amankou et al., 2024; Matsui, 2024; Xiao et al., 2023).

Omni-channel is a relevant concept to dual-channel, which integrates physical store sales, online sales, and mobile e-commerce channels to meet consumers' needs for purchasing products anytime, anywhere, and providing a seamless consumer experience. However, unlike dual-channel emphasizes the simultaneous use of direct and distribution channels, omni-channel emphasizes integration and complementarity across different channels. Saghiri et al. (2017) propose a concept framework for an omni-channel system based on three dimensions: channel stage, channel type, and channel agent, discussing key factors—integration and visibility—that support the implementation of an omni-channel framework. Manufacturer encroachment is also an important topic related to dual-channel, Gao et al. (2021) show if cost information asymmetry is considered in dual-channel, cannot hurt but benefit the retailer.

Research on green supply chain management includes studies on influencing factors, supply chain decisions, supply chain design, and coordination. The influencing factors of green supply chain management contain internal and external factors. Sarkis (2003) identifies numerous factors affecting green supply chain management, including product green degree, corporate market advantage, and investments in environmental innovation. Testa and Iraldo (2010) highlight those internal factors of green supply chain management stem from enterprise-led strategic processes, while external factors primarily involve stakeholder pressures. Green et al. (2012) find that, in addition to their own interests, customer demand and government regulations are also key drivers for companies to implement green supply chain management practices. Govindan et al. (2014) conduct field surveys on supply chain management and its related departments, identifying numerous barriers during implementation. He et al. (2024) investigate how tax enforcement affects corporate environmental investment, and reveal that tougher tax enforcement significantly lowers corporate environmental investment.

Many scholars utilize game theory to study decision-making in green supply chain management (Nagurney and Toyasaki, 2003; Altintas et al., 2008; Atasu et al., 2008; Ghosh and Shah, 2012; Ala-Harja and Helo, 2015). Dey and Saha (2018) analyze manufacturers' green degree decisions and wholesale pricing decisions using Stackelberg game models under three procurement modes, concluding that retailer procurement decisions are pivotal but not entirely motivating for manufacturers to produce green products. Xi and Lee (2015) study green degree decision-making in manufacturer-led Stackelberg game models of green products in traditional retail channels. Li et al. (2016) investigate decision-making on pricing and green degree by manufacturers and retailers under uniform pricing strategies using Stackelberg models, showing that the decision of manufacturers to sell green products through direct channels depends on the magnitude of green costs. Wang et al. (2023) incorporate demand forecast information sharing between the retailer and the manufacturer in the green supply chain and examine three cases: centralized decision, decentralized decision with and without demand forecast information sharing. They find that demand forecast information sharing benefits the manufacturer while hurting the retailer.

Some scholars discuss the design of green supply chains using multi-objective optimization methods (Kadziński et al., 2017; Liou et al., 2016). To coordinate the green supply chain, Bernstein and Federgruen (2005) explore the decentralized decisions for manufacturers based on stochastic demand functions in a three-tier supply chain, and find that retailers and manufacturers can maximize profits through contract design. Swami and Shah (2013) study channel conflicts in green supply chain management, and concludes that resolving conflicts between manufacturers and retailers improves the management of green supply chains. Jian et al. (2021) consider the manufacturer's fairness concern based on the consideration of the retailer's sales effort, and design of a green closed-loop supply chain with profit-sharing contract coordination fairness. Wang et al. (2020) also incorporate green manufacturers' fairness concerns to explore the decisions and coordination of green e-commerce supply chain, and find that unlike traditional offline and dual-channel supply chains, the manufacturer's behavior in response to fairness concerns can result in the decline both in product green degree and system efficiency but has no impact on service level.

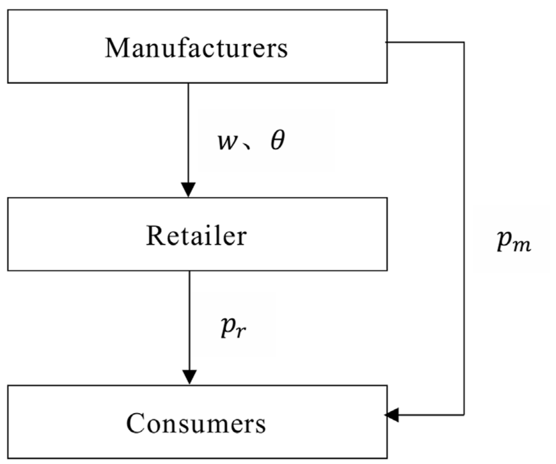

FIGURE 1
Supply chain structure diagram.

There has been a trend to consider green factors in dual-channel in recent years such as green technologies, green innovation, and government monitoring (Gao et al., 2020; Pa and Sarkar, 2021; Mahmoudi et al., 2020). However, few literatures have incorporated green degree decisions into dual-channel and studied the coordination of dual-channel supply chains through green degree decision and pricing strategies.

3 Model

We consider a dual-channel supply chain consisting of a green product manufacturer and a retailer. The manufacturer produces one type of green product, which is sold either through the retailer or via its direct channel. We discuss two cases: The manufacturer makes the pricing decision only (P), and the manufacturer jointly decides the price and the green degree of the product (PG). Both cases include decentralized and centralized decision scenarios. In the decentralized decision scenario (D), the manufacturer decides the direct channel price (and the green degree in case PG) first, and then the retailer decides the indirect channel price. We assume the wholesale price is exogenously given, and relax this assumption in Section 5. In the centralized decision scenario (C), the manufacturer decides the direct channel price and the indirect channel price (and also the green degree in case PG) together. In total, we consider four subgames: P-D, PG-D, P-C, and PG-C. The supply chain structure is shown in Figure 1.

We have the following assumptions:

a. The demand functions for both channels are linear functions of the green degree and the price. As environmental awareness increases, consumers show a preference for products with a higher green degree. If the green degree is not considered, the demand functions for the direct and indirect channels are Equations 1, 2:

$$D_m = (1-\rho)a - b_1 p_m + b_2 p_r \tag{1}$$

$$D_r = \rho a - b_1 p_r + b_2 p_m \tag{2}$$

If the green degree is considered, the demand functions for the direct and indirect channels are Equations 3, 4:

$$D_m = (1-\rho)a - b_1 p_m + b_2 p_r + \beta_m \theta \tag{3}$$

$$D_r = \rho a - b_1 p_r + b_2 p_m + \beta_r \theta \tag{4}$$

Where D_m and D_r represent the market demand in the direct and indirect channel, respectively; a is the potential market demand; ρ is the potential market share of indirect channel ($0 < \rho < 1$), and $1-\rho$ is the potential market share of direct channel. p_m and p_r are the prices in the direct channel and indirect channel, respectively. b_1 is the marginal channel demand with respect to price, and b_2 is the cross–price sensitivity coefficient, indicating the impact of the price in one channel on the demand in the other channel, where $b_1 > b_2$ signifies that the effect of a channel′s own price is greater than the cross–price effect. θ indicates the green degree of the product. β_m and β_r represent consumers' environmental awareness in the direct channel and indirect channel, respectively, where $b_1 > \beta_r$ and $b_1 > \beta_m$ indicate that the impact of price on demand is greater than that of the green degree on demand (Li et al., 2016).

b. $p_r \geq w \geq c$ and $p_m \geq c$, where c is the unit manufacturing cost of the product, and c is normalized to 0. p_r is the retailer′s indirect channel price, p_m is the manufacturer′s direct channel price, and w is the wholesale price set by the manufacturer, which is assumed to be given (we relax this assumption in our model extension).
c. Green products do not alter the manufacturer's traditional marginal cost, but the manufacturer must invest additional green costs, which is denoted as $C(\theta) = \frac{1}{2}\eta\theta^2$, where η is the cost coefficient per unit of green degree (Saghiri et al., 2017).
d. At the same green degree, green products have a greater impact on customers in the indirect channel than on customers in the direct channel. This is because customers usually have a deeper understanding of the product's green degree in the indirect channel, making them more attracted by the green degree of the product compared to the direct channel, i.e., $\beta_r > \beta_m$.
e. The potential market demand a is significantly greater than the other parameters in the model.

Furthermore, the model must satisfy two constraints simultaneously: the demand in both the direct and indirect channels must be non-negative, and the profits in both the direct and indirect channels must be non-negative, and the green degree must also be non-negative. In other words, this is represented by (Equation 5):

$$w \leq p_r, 0 \leq p_m, 0 \leq \theta \text{ and } 0 \leq D_r, 0 \leq D_m \tag{5}$$

3.1 Manufacturer decides on the price in decentralized decision-making model (subgame P-D)

When the manufacturer only decides on the price in the decentralized decision scenario, the manufacturer chooses the direct channel price p_m at stage one, and the retailer determines the indirect channel price p_r at stage two. The profits in the direct and indirect channel are denoted as π_m and π_r, respectively, and we have Equations 6, 7:

$$\begin{aligned}\pi_m &= wD_r + p_m D_m \\ &= w(\rho a - b_1 p_r + b_2 p_m) + p_m[(1-\rho)a - b_1 p_m + b_2 p_r]\end{aligned} \tag{6}$$

$$\pi_r = (p_r - w)D_r = (p_r - w)(\rho a - b_1 p_r + b_2 p_m) \tag{7}$$

By applying the backward induction method of Stackelberg game, we can derive the optimal solutions for subgame P-D as stated in the following proposition.

Proposition 1. In subgame P-D, we have:

(I) When $0 < w < \frac{2ab_1b_2(1-\rho)+4ab_1^2\rho-ab_2^2\rho}{4b_1^3-4b_1b_2^2}$, the optimal direct channel and indirect channel prices and demands are $p_{md}^* = \frac{2b_1b_2w+2ab_1+(ab_2-2ab_1)\rho}{4b_1^2-2b_2^2}$, $p_{rd}^* = \frac{4b_1^3w+2ab_1b_2+(4ab_1^2-ab_2^2-2ab_1b_2)\rho}{4(2b_1^2-b_2^2)b_1}$, $D_{md}^* = \frac{2ab_1+(ab_2-2ab_1)\rho}{4b_1}$ and $D_{rd}^* = \frac{2ab_1b_2-4b_1^3w+4b_1b_2^2w+(4ab_1^2-ab_2^2-2ab_1b_2)\rho}{4(2b_1^2-b_2^2)}$, respectively.

(II) When $w \geq \frac{2ab_1b_2(1-\rho)+4ab_1^2\rho-ab_2^2\rho}{4b_1^3-4b_1b_2^2}$, the indirect channel demand $D_{rd}^* = 0$, and the optimal direct channel price is $p_{md}^* = \frac{a(1-\rho)}{2b_1}$.

Proposition 1 indicates that when the wholesale price *(w)* is below a certain threshold, the retailer will establish an indirect channel; otherwise, introducing the indirect channel is not profitable for the retailer and thus the retailer will exit the market. Additionally, as the potential market share of indirect channel (ρ) increases, the optimal price and demand from the indirect channel rise ($ab_2 - 2ab_1 < 0$), while the optimal price and demand from the direct channel decrease ($4ab_1^2 - ab_2^2 - 2ab_1b_2 > 0$). Therefore, changes in the wholesale price w and the potential market share of indirect channel (ρ) do not necessarily lead to additional profit for the manufacturer, but an increase in the wholesale price (w), together with a decrease in the potential market share of indirect channel (ρ), will certainly reduce the retailer's profit.

3.2 Manufacturer decides on the price in centralized decision-making model (subgame P-C)

When the manufacturer only decides on the price in the centralized decision scenario, both parties jointly decide on the direct channel price p_m and the indirect channel price p_r. The total profit for the dual-channel is Equation 8:

$$\begin{aligned}\pi_c &= p_r D_r + p_m D_m \\ &= p_r(\rho a - b_1 p_r + b_2 p_m) + p_m[(1-\rho)a - b_1 p_m + b_2 p_r]\end{aligned} \tag{8}$$

By employing the method of backward induction, we can derive the equilibrium solutions for subgame P-C described in Proposition 2.

Proposition 2. In subgame P-C, the optimal prices and demands for direct and indirect channel are $p_{mc}^* = \frac{ab_1+(ab_2-ab_1)\rho}{2(b_1^2-b_2^2)}$, $p_{rc}^* = \frac{ab_2+(ab_1-ab_2)\rho}{2(b_1^2-b_2^2)}$, $D_{mc}^* = \frac{a(1-\rho)}{2}$ and $D_{rc}^* = \frac{a\rho}{2}$, *respectively.*

Proposition 2 indicates that, in subgame P-C, as the potential market share of indirect channel (ρ) increases, the optimal price and demand for the direct channel decrease, while the optimal price and demand for the indirect channel increase ($b_1 > b_2$), which is consistent with the conclusions in subgame P-D. When the manufacturer only decides on the price, the demand for the direct channel under decentralized decision-making is consistently greater than that under centralized decision-making. When the wholesale price exceeds a certain threshold ($\frac{ab_2(1-\rho)+ab_1\rho}{2(b_1^2-b_2^2)}$), the optimal prices of both the direct and indirect channels in decentralized decision-making are higher than those in centralized decision-making. However, when the wholesale price surpasses another threshold ($\frac{2ab_1b_2(1-\rho)+ab_2^2\rho}{4b_1^3-4b_1b_2^2}$), the demand for the indirect channel under decentralized decision-making becomes lower than the demand for the indirect channel under centralized decision-making.

3.3 Manufacturer decides on the price and green degree in decentralized decision-making model (subgame PG-D)

In subgame PG-D, the manufacturer decides the direct channel price p_m and the green degree θ at stage one, and the retailer determines the indirect channel price p_r at stage two. The profit functions of both players are Equations 9, 10:

$$\begin{aligned}\pi_m &= wD_r + p_m D_m - C(\theta) \\ &= w(\rho a - b_1 p_r + b_2 p_m + \beta_r \theta) \\ &\quad + p_m[(1-\rho)a - b_1 p_m + b_2 p_r + \beta_m \theta] - \frac{1}{2}\eta\theta^2\end{aligned} \tag{9}$$

$$\pi_r = (p_r - w)D_r = (p_r - w)(\rho a - b_1 p_r + b_2 p_m + \beta_r \theta) \tag{10}$$

By employing the method of backward induction, we can derive the equilibrium solutions for subgame PG-D described in Proposition 3.

Proposition 3. In subgame PG-D, we can obtain the equilibrium solutions for the game as follows (the expression of $p_{m1}, p_{r1}, \theta_1, a_1, \eta_1$ and η_2 are shown in Supplementary Appendix):

(I) When $0 < a < a_1$, the following conditions hold:
- (i) When $0 < \eta \leq \eta_1$ the direct channel demand $D_m^d = 0$, and the optimal price of the indirect channel and green degree are $p_r^d = \frac{2a\eta\rho+2b_1\eta w+\beta_r^2 w}{4b_1\eta}$ and $\theta^d = \frac{\beta_r w}{2\eta}$, respectively.
- (ii) When $\eta_1 < \eta < \eta_2$, the optimal prices for the direct and indirect channels and the optimal green degree are $p_m^d = p_{m1}$, $p_r^d = p_{r1}$ and $\theta^d = \theta_1$, respectively.
- (iii) When $\eta \geq \eta_2$, the indirect channel demand $D_r^d = 0$, and the optimal price of the direct channel and green degree are $p_m^d = \frac{a\eta(1-\rho)}{2b_1\eta-\beta_m^2}$ and $\theta^d = \frac{a\beta_m(1-\rho)}{2b_1\eta-\beta_m^2}$, respectively.

(II) When $a \geq a_1$, the following conditions hold:
- (i) When $0 < \eta \leq \eta_1$, the *direct* channel demand $D_m^d = 0$, and the optimal price of the indirect channel and green degree are $p_r^d = \frac{2a\eta\rho+2b_1\eta w+\beta_r^2 w}{4b_1\eta}$ and $\theta^d = \frac{\beta_r w}{2\eta}$, respectively.
- (ii) When $\eta > \eta_1$, *the* optimal prices for the direct and indirect channels and the optimal green degree are $p_m^d = p_{m1}$, $p_r^d = p_{r1}$ and $\theta^d = \theta_1$, respectively.

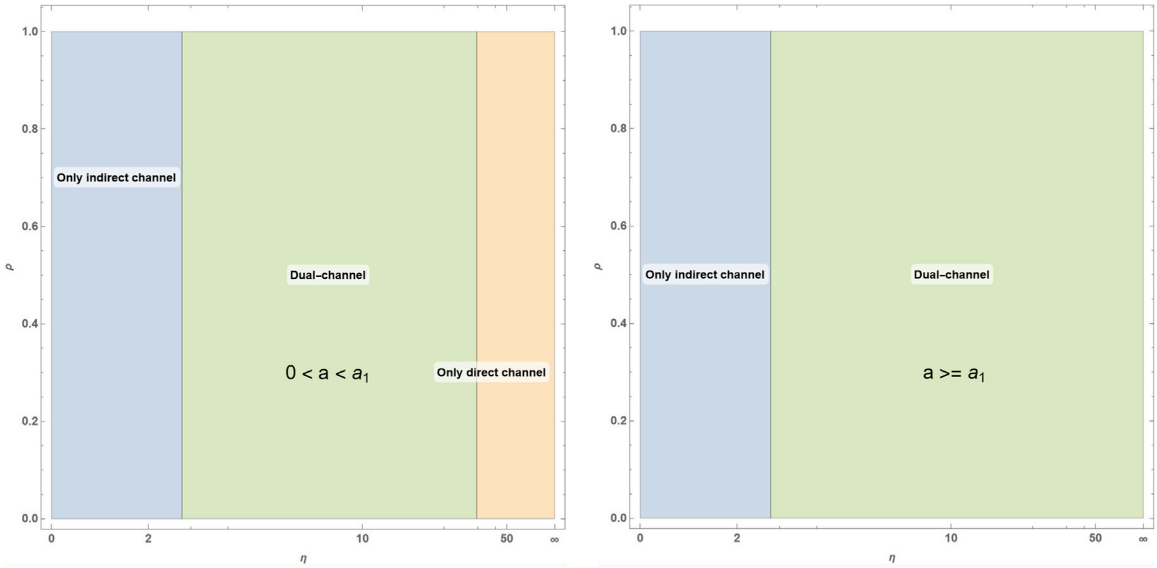

FIGURE 2
The outcomes of subgame PG-D, where $b_1 = 6$, $b_2 = 5$, $\beta_r = 4$, $\beta_m = 3$, $w = 10$, $\rho = 4$, $a = 15 < a_1$.

The above result is shown in Figure 2.

Proposition 3 (I) indicates that when potential market demand is low ($0 < a < a_1$), the channel strategy transitions from a single indirect channel to a dual-channel strategy and eventually to a single direct channel as the green cost coefficient η increases. This is because when the green cost coefficient is low ($0 < \eta \leq \eta_1$), a lower wholesale price makes the single indirect channel more efficient. However, when the green cost coefficient is moderate ($\eta_1 < \eta < \eta_2$), the lower wholesale price and the demand from the single indirect channel cannot compensate for the green cost. At this point, due to the presence of the cross-price sensitivity coefficient b_2, a dual-channel strategy can attract more consumers and offset the increased green cost. When the green cost is very high ($\eta \geq \eta_2$), and given that the potential market demand is already low, the additional demand from the dual-channel is still insufficient to cover the green cost. As a result, the manufacturer can only establish a single direct channel, compensating for the high green cost by increasing unit profit ($p_m > w$). Proposition 3 (II) indicates that when market demand is high ($a \geq a_1$), the channel strategy will shift from a single indirect channel to a dual-channel strategy as the green cost coefficient η increases. Since the high potential market demand is sufficient to accommodate both channels without causing excessive competition, the single direct channel strategy disappears, being replaced by the more efficient dual-channel strategy when the green cost coefficient η is high. Then we also derive the following results:

Corollary 1. In subgame PG-D, when dual-channel exist ($0 < a < a_1, \eta_1 < \eta < \eta_2$ or $a \geq a_1, \eta > \eta_1$), we have (the expression of θ_1^* and θ_2^* are shown in Supplementary Appendix):

(I) $\frac{d\pi_r}{d\theta} > 0$ when (i) $0 < a < a_1, \eta_1 < \eta < \eta_2, \theta > \theta_1^*$,or (ii) $a \geq a_1, \eta > \eta_1, \theta > 0$.
(II) $\frac{d\pi_m}{d\theta} > 0$ when $\theta > \theta_2^*$, and $\frac{d\pi_m}{d\theta} < 0$ when $0 < \theta < \theta_2^*$.

Corollary 1 indicates that, in the dual-channel scenario of subgame PG-D, when the green cost coefficient η is not high, the retailer's profit decreases as the green degree θ increases. However, when the green cost coefficient η is high, the retailer's profit increases with the green degree θ. For the manufacturer, as the green degree θ increases, the profit from the direct channel first decreases and then increases. Therefore, we conclude that when the green degree θ of the product is relatively high ($\theta > max[\theta_1^*, \theta_2^*]$), enhancing the green degree not only benefits the manufacturer, but also increases the profits of the retailer (π_m and π_r), which leads to a win-win situation.

3.4 Manufacturer decides on both price and green degree in centralized decision-making model (subgame PG-C)

In subgame PG-C, both parties jointly decide on the direct channel price p_m , the green degree θ, and the indirect channel price p_r. The total profit for the dual-channel is Equation 11:

$$\begin{aligned}\pi^c &= p_r D_r + p_m D_m - C(\theta)\\ &= p_r(\rho a - b_1 p_r + b_2 p_m + \beta_r \theta)\\ &\quad + p_m[(1-\rho)a - b_1 p_m + b_2 p_r + \beta_m \theta] - \frac{1}{2}\eta\theta^2 \qquad (11)\end{aligned}$$

By employing the method of backward induction, we can derive the equilibrium solutions for subgame PG-C as described in the following proposition.

Proposition 4. In subgame PG-C, we can obtain the equilibrium solutions for the game as follows (the expression of $p_{m2}, p_{r2}, \theta_2, \eta_3$ and η_4 are shown in Supplementary Appendix):

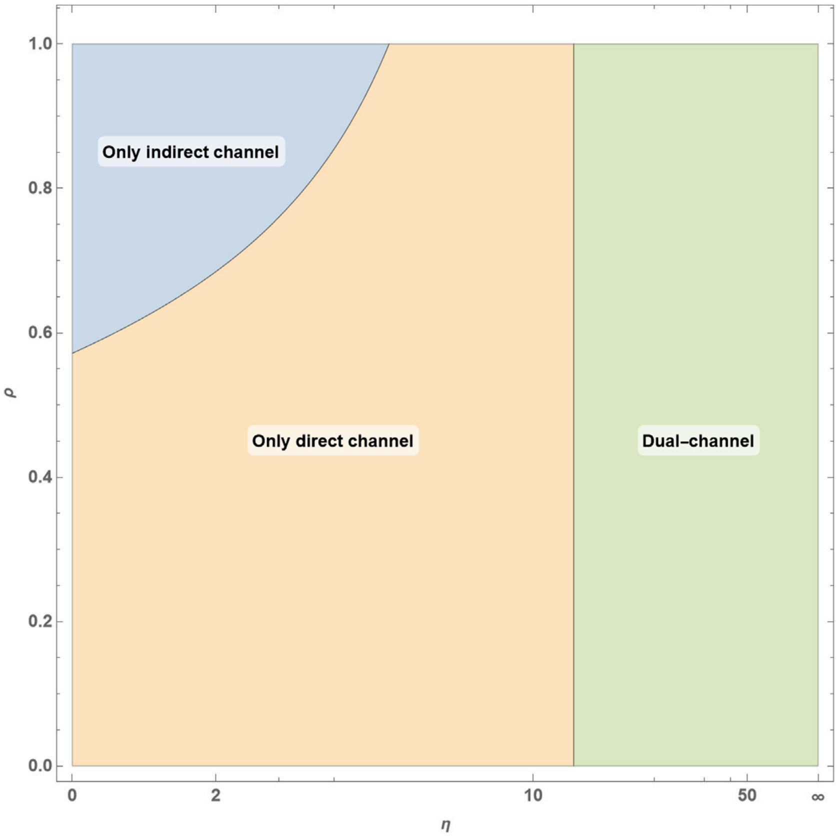

FIGURE 3
The outcomes of subgame PG-C, where $b_1 = 6$, $b_2 = 5$, $\beta_r = 4$, $\beta_m = 3$.

(I) When (a) $0 < \rho \le \frac{\beta_r}{\beta_m+\beta_r}, 0 < \eta \le \eta_3$ or (b) $\frac{\beta_r}{\beta_m+\beta_r} < \rho < 1, \eta_4 \le \eta \le \eta_3$, the indirect channel demand $D_r^c = 0$, and the optimal direct channel price and green degree are $p_m^c = \frac{a\eta(1-\rho)}{2b_1\eta-\beta_m^2}$ and $\theta^c = \frac{a\beta_m(1-\rho)}{2b_1\eta-\beta_m^2}$, respectively.

(II) When $\frac{\beta_r}{\beta_m+\beta_r} < \rho < 1, 0 < \eta < \eta_4$, the direct channel demand $D_m^c = 0$, and the optimal indirect channel price and green degree are $p_r^c = \frac{a\eta\rho}{2b_1\eta-\beta_r^2}$ and $\theta^c = \frac{a\beta_r\rho}{2b_1\eta-\beta_r^2}$, respectively

(III) When $0 < \rho < 1, \eta > \eta_3$, the optimal prices for the direct and indirect channels and green degree are $p_m^c = p_{m2}$, $p_r^c = p_{r2}$ and $\theta^c = \theta_2$, respectively.

The above result is shown in Figure 3.

Proposition 4 indicates that when the green cost coefficient η is high ($\eta > \eta_3$), channel members will opt to supply products through a dual-channel strategy, as this approach simultaneously increases the demand for both channels, thereby offsetting the higher green costs. When the green cost coefficient η is low ($\eta < \eta_4$), the potential market share of indirect channel ρ determines whether the direct or indirect channel alone supplies products to consumers. However, when the green cost coefficient η is moderate ($\eta_4 \le \eta \le \eta_3$), only the direct channel supplies products to consumers, as the indirect channel generates a negative demand. Therefore, we derive the following insights:

Corollary 2. *In subgame PG-D, when dual-channel exist ($0 < \rho < 1, \eta > \eta_3$), we have:*

(I) Compare subgame PG-C and subgame PG-D, we have: $\frac{d\theta^d}{d\rho} < 0$, $\frac{d\theta^c}{d\rho} > 0$.

(II) *In* subgame PG-D, *we have:* $\frac{dp_m^d}{d\rho} < 0$, $\frac{dp_r^d}{d\rho} < -\frac{dp_m^d}{d\rho}$.

(III) In subgame PG-C, we have: $\frac{dp_r^c(\theta)}{d\theta} > \frac{dp_m^c(\theta)}{d\theta} > 0$.

Corollary 2 (I) indicates that, as the potential market share of indirect channel (ρ) increases, the manufacturer will reduce the green degree (θ) under subgame PG-D, while increase θ under subgame PG-C. This is because the double marginalization does not exist in subgame PG-C, the increase in the potential market share of indirect channel (ρ) benefits the manufacturer directly. However, in subgame PG-D, as the potential market share of indirect channel (ρ) increases, the manufacturer cannot offset the green cost by attracting consumers with lower direct channel price (p_m) and must reduce θ to lower green costs. Corollary 2 (II) indicates that, in subgame PG-D, the direct channel price (p_m) decreases as ρ increases. Moreover, compared to the indirect channel price (p_r), the direct channel price (p_m) is more sensitive to the changes in the potential market share of indirect channel (ρ). Corollary 2 (III) indicates that, in subgame PG-C, the indirect channel price (p_r) is more sensitive to changes in the green degree (θ) than the direct channel price (p_m) is. This implies that since β_r is greater than β_m, in subgame PG-C, an increase in the green degree (θ) can lead to higher indirect channel demand (D_r^c) and increase the retailer's profit (π_r) when the wholesale price (w) remains constant.

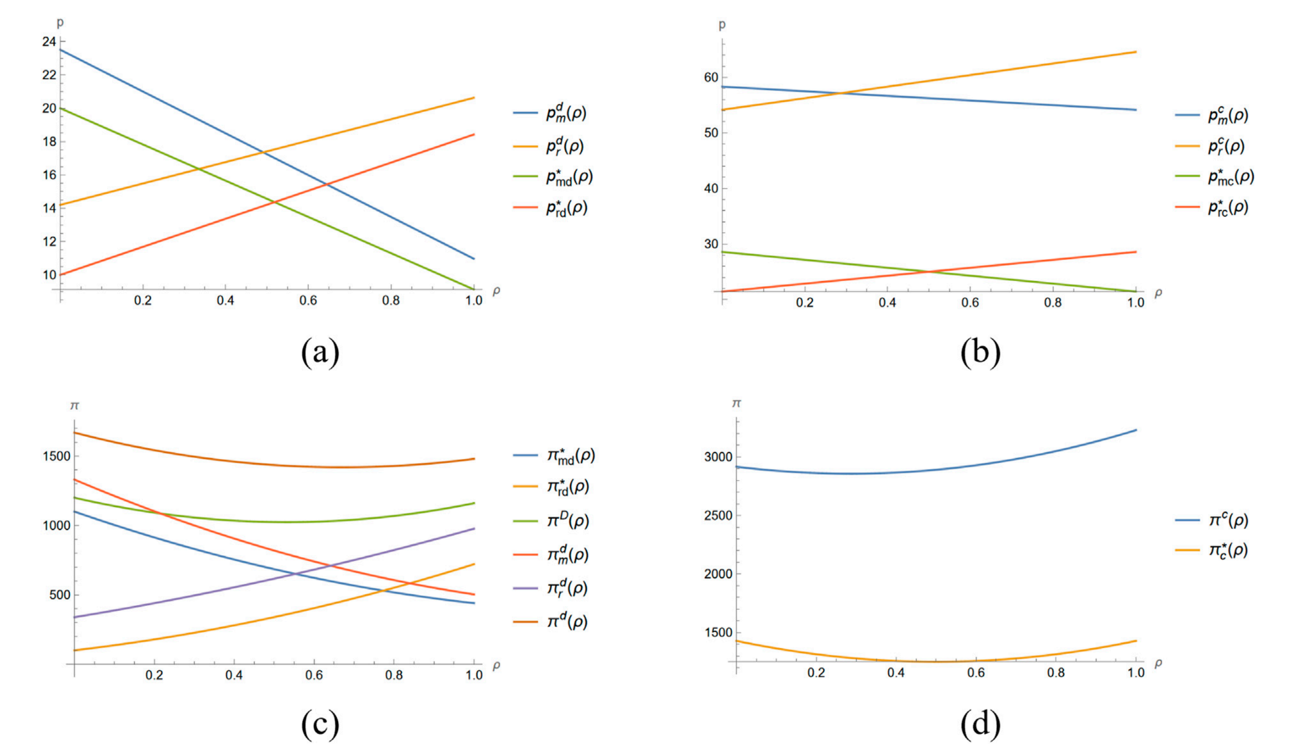

FIGURE 4
The effects of the potential market share of indirect channel on prices and profits, where $a = 100$, $w = 5$, $b_1 = 4$, $b_2 = 3$, $\beta_r = 2$, $\beta_m = 1$, $\eta = 4$, $0 < \rho < 1$.

4 Numerical study analysis

In this section, we conduct a numerical analysis to compare the profits and prices of the manufacturer and retailer in case P and case PG, respectively, which illustrates the impact of the green cost coefficient (η) and consumers' environmental awareness in different channels (β_r, β_m) on the green degree, prices, and profits (θ, p_r, p_m, π_r and π_m).

4.1 The impact of manufacturers' decisions on green degree

By analyzing the optimal prices and profits of the manufacturer and retailer under decentralized and centralized decision-making, we can identify the effects of the potential market share of indirect channel (ρ) on prices and profits in different subgames as shown in Figure 4.

In Figure 4, P_{md}^*, P_{rd}^*, π_{md}^*, π_{rd}^*, and π^D represent the manufacturer's direct price, the retailer's indirect channel price, the manufacturer's profit, the retailer's profit, and the total profit in subgame P-D, respectively. Similarly, P_m^d, P_r^d, π_m^d, π_r^d, and π^d represent corresponding equilibrium results in subgame PG-D. P_{mc}^*, P_m^c, P_{rc}^*, P_r^c, π_c^*, and π^c represent the manufacturer's direct price, the retailer's indirect channel price, and the total profit in subgames P-C and PG-C, respectively.

Figure 4A, B show that, as the potential market share of indirect channel (ρ) increases, the indirect channel price (p_r^d, p_{rd}^*, p_r^c and p_{rc}^*) increase while the direct channel price (p_m^d, p_{md}^*, p_m^c and p_{mc}^*) decrease in all subgames. Figure 4C indicates that under decentralized decision-making, as ρ increases, the profits for both the direct and indirect channel (π_m^d, π_{md}^*, π_r^d and π_{rd}^*), as well as total profits (π^d and π^D) in different scenarios show the same tendency. In particular, as ρ increases, retailer's profit (π_r^d and π_{rd}^*) increase while manufacturer's profit (π_m^d and π_{md}^*) decrease. Besides, when ρ exceeds a certain threshold, manufacturer's profits (π_m^d and π_{md}^*) are lower than retailer's profits (π_r^d and π_{rd}^*). Figure 4D illustrates that under centralized decision-making, total profits (π^c and π_c^*) initially decreases and then increase with ρ, which is consistent with the trend under decentralized decision-making.

Regarding whether the manufacturer decides on green degree (θ) or not, we find that when green degree is considered in the decision-making process, both cases yield higher values for the manufacturer, retailer, and total profits. Comparing Figure 4C with Figure 4D, it shows that the total profits under centralized decision-making is always higher than those under decentralized decision-making.

4.2 The impact of the green cost coefficient on green degree, prices, and profits

We illustrate the effects of the green cost coefficient (η) on green degree, prices, and profits in subgames PG-D and PG-C in the following figures.

In Figure 5, P_m^d, P_m^c, P_r^d, P_r^c, θ^d, θ^c represent the manufacturer's direct price, the retailer's indirect channel price and the green degree in subgames PG-D and PG-C, respectively.

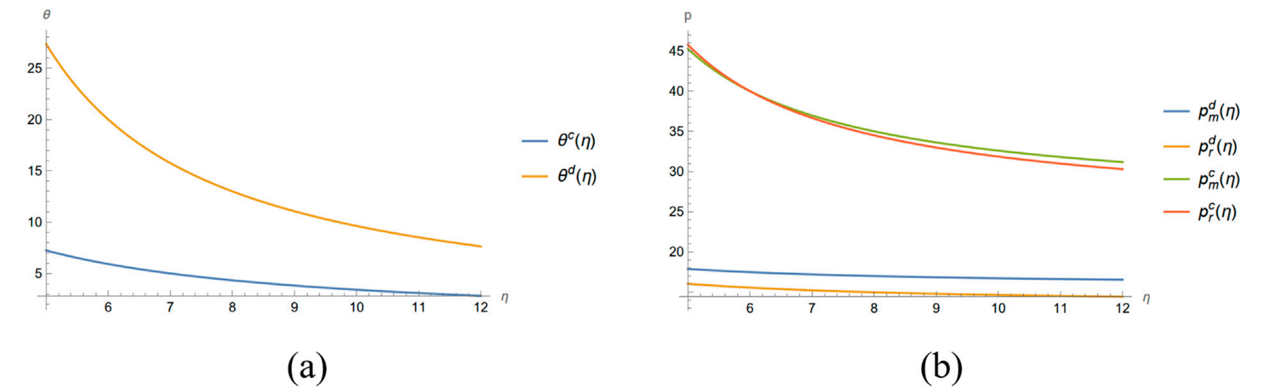

FIGURE 5
The effect of the green cost coefficient on green degree and prices, where $\rho = 0.4$, $5 \leq \eta \leq 12$.

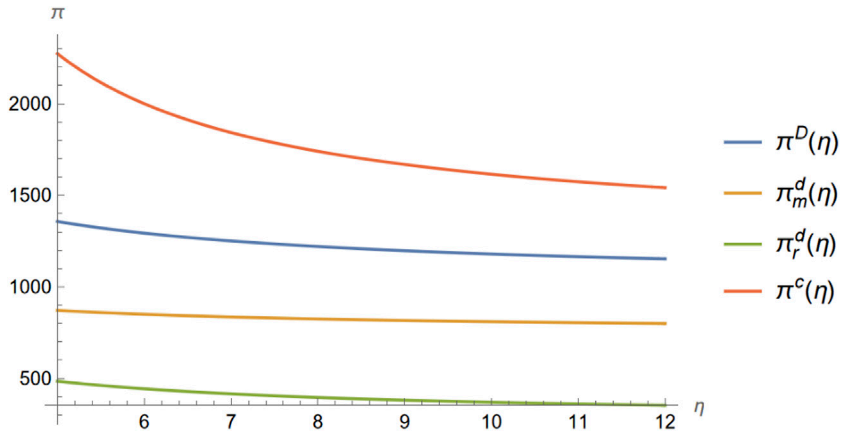

FIGURE 6
The impact of the green cost coefficient on profits, where $\rho = 0.4$, $5 \leq \eta \leq 12$.

In Figure 6, π_m^d, π_r^d, π^D represent the manufacturer's profit, the retailer's profit, the total profit in subgame PG-D, respectively, and π^c represent the total profit in subgame PG-C.

Figures 5, 6 illustrate the impact of η on green degree (θ^d, θ^c), direct price, and indirect channel price (p_m^d, p_m^c, p_r^d and p_r^c). Typically, in subgames PG-D and PG-C, these variables decrease as η increases, as shown in Figure 6. Figure 5B further indicates that when η is relatively small, the difference in channel prices between centralized and decentralized decision-making (p_m^c and p_m^d; p_r^c and p_r^d) is significant. However, as η increases, this difference gradually diminishes.

4.3 The impact of consumers' environmental awareness in different channels on green degree and prices

We illustrate the effects of consumers' environmental awareness in different channels (β_m and β_r) on green degree (θ^d and θ^c), and the optimal pricing of channel members are shown in Figure 7.

The demand functions indicate that consumers' environmental awareness in different channels (β_m and β_r) greatly influence the dual-channel demand. Therefore, we can vary the values of β_m and β_r to discuss their impacts on the green degree (θ^d and θ^c) and prices (p_m^d, p_m^c, p_r^d and p_r^c) in different cases. Figure 7A shows the optimal green degree (θ^d and θ^c) choices increase with the β_m and β_r. In Figure 7B, we find that both direct and indirect channel prices (p_m^d, p_m^c, p_r^d and p_r^c) increase with the β_m and β_r.

4.4 The combined impact of consumers' environmental awareness in direct channel and green cost coefficient on profits

We illustrate the combined effects of green cost coefficient (η) and consumers' environmental awareness in direct channel (β_m) on profits in Figure 8.

Figure 8 indicates that manufacturer's profit (π_m^d) exceeds retailer's profit (π_r^d), and total profit under centralized decision exceeds that under decentralized decision (π^c and π^D); especially when consumers' environmental awareness in direct channel (β_m) is

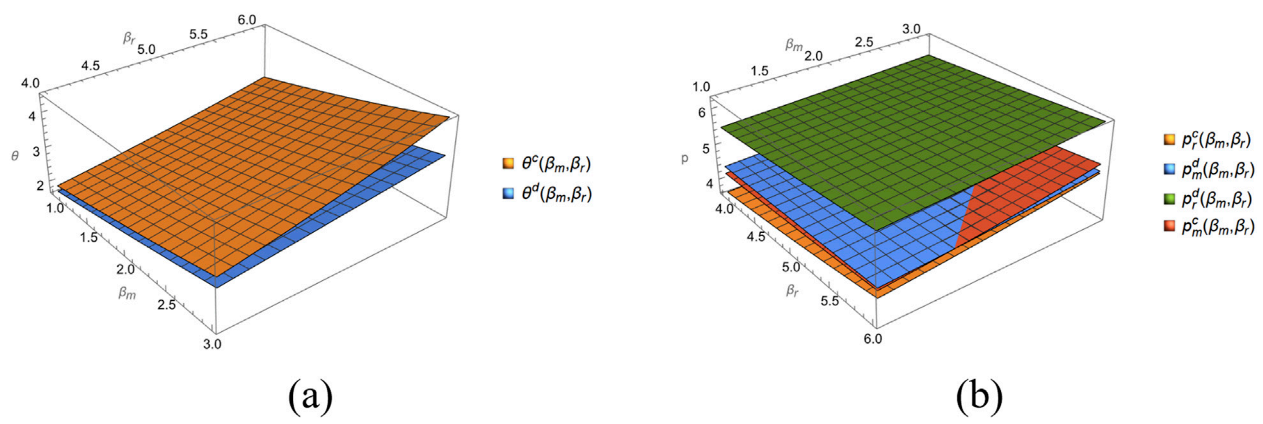

FIGURE 7
The impact of consumers' environmental awareness in different channels on green degree and prices, where $a = 100$, $w = 5$, $b_1 = 10$, $b_2 = 3$, $\eta = 10$, $\rho = 0.4$, $1 \le \beta_m \le 3$, $4 \le \beta_r \le 6$.

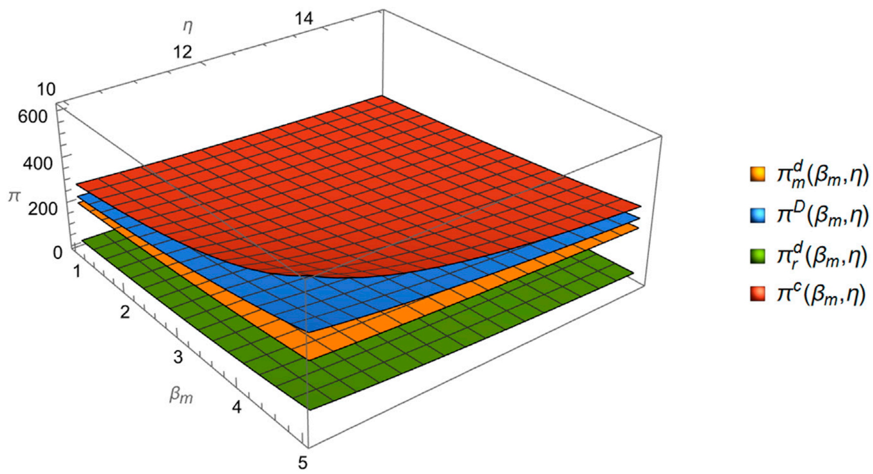

FIGURE 8
The combined impact of consumers' environmental awareness in direct channel and green cost coefficient on profit, where $a = 100$, $w = 5$, $b_1 = 10$, $b_2 = 3$, $\beta_r = 9$, $\rho = 0.4$, $1 \le \beta_m \le 5$, $10 \le \eta \le 15$.

high, total profit under centralized decision is significantly higher than under decentralized decision (π^c and π^D). On the other hand, the impact of the green cost coefficient (η) on channel profits in subgames PG-D and PG-C depends on the level of consumers' environmental awareness in direct channel (β_m). When consumers' environmental awareness in direct channel (β_m) is low, the impact of η on profit is relatively small; however, when consumers' environmental awareness in direct channel (β_m) is high, a decrease in the green cost coefficient (η) leads to an increasing trend in profits across all channels. Thus, the total profit under centralized decision-making shows a particularly significant increase. Therefore, under centralized decision-making, when consumers' environmental awareness in direct channel is relatively low, the influence of the green cost coefficient (η) on channel profits is not pronounced; but when consumers' environmental awareness in direct channel is high, channel profits rise significantly as the green cost coefficient decreases.

5 Model extension

In this section, we consider the wholesale price (w) as a decision variable in subgames P-D and PG-D, and analyze how the wholesale price set by the manufacturer influences the retailer's decisions regarding the introduction of the indirect channel, the indirect channel price and profit under decentralized decision-making.

5.1 Manufacturer decides on wholesale prices in subgame P-D

In subgame P-D, the manufacturer first determines the direct channel price and the wholesale price for the indirect channel, and then the retailer decides the indirect channel price (if this channel is introduced). By employing the method of backward induction, we can derive the equilibrium solutions in Proposition 5.

Proposition 5. *In subgame P-D, we can obtain the equilibrium solutions as follows:*

The optimal price for the direct and indirect channels and the optimal wholesale price are $p^*_{md} = \frac{ab_1(1-\rho)+ab_2\rho}{2(b_1^2-b_2^2)}$, $p^*_{rd} = \frac{2ab_1b_2(1-\rho)+3ab_1^2\rho-ab_2^2\rho}{4(b_1^3-b_1b_2^2)}$ and $w^*_d = \frac{ab_2(1-\rho)+ab_1\rho}{2(b_1^2-b_2^2)}$, respectively.

Proposition 5 indicates that, in subgame P-D, when the manufacturer can determine the optimal wholesale price, both direct and indirect channels will always exist in the market, regardless of the potential market share of indirect channel. This is because when the manufacturer can determine the optimal wholesale price, it is possible to balance the profitability of both channels under any potential market share of indirect channel, ensuring the coexistence of dual-channel. Moreover, the dual-channel strategy increases demand in both channels simultaneously, further enhancing the profitability of all channel members. Therefore, we can draw the following insights:

Corollary 3. *In subgame P-D, we have:*

(I) $\frac{\partial w}{\partial a} > 0, \frac{\partial \pi_m}{\partial a} > 0, \frac{\partial p_r}{\partial a} > 0, \frac{\partial \pi_r}{\partial a} > 0$.
(II) when $0 < \rho \leq \frac{2b_1}{3b_1-b_2}$, $\frac{\partial w}{\partial \rho} > 0, \frac{\partial \pi_m}{\partial \rho} \leq 0, \frac{\partial p_r}{\partial \rho} > 0, \frac{\partial \pi_r}{\partial \rho} > 0$; when $\frac{2b_1}{3b_1-b_2} < \rho < 1$, $\frac{\partial w}{\partial \rho} > 0, \frac{\partial \pi_m}{\partial \rho} > 0, \frac{\partial p_r}{\partial \rho} > 0, \frac{\partial \pi_r}{\partial \rho} > 0$;
(III) $\frac{\partial w}{\partial b_1} < 0, \frac{\partial \pi_m}{\partial b_1} < 0, \frac{\partial p_r}{\partial b_1} < 0, \frac{\partial \pi_r}{\partial b_1} < 0$.
(IV) $\frac{\partial w}{\partial b_2} > 0, \frac{\partial \pi_m}{\partial b_2} > 0, \frac{\partial p_r}{\partial b_2} > 0$.

Corollary 3 indicates that, when the expansion of potential market demand (a) or the reduction of marginal channel demand (b_1) leads to an increase in the wholesale price w, both the manufacturer and the retailer benefit from the growth in demand (D_m and D_r), resulting in increased profits for both parties (π_m and π_r). When the increase in wholesale price (w) is due to a rise in the cross-price sensitivity coefficient (b_2), the direct channel profit (π_m) increases, but the sharp increase in the wholesale price (w) offsets the increase in indirect channel price (p_r) and product demand (D_r), resulting in unchanged indirect channel profit (π_r). When the potential market share of indirect channel (ρ) is large, with the further increase of the potential market share of indirect channel (ρ), both the manufacturer and the retailer will be better off. However, when the potential market share of indirect channel is below the threshold $\left(\rho \leq \frac{2b_1}{3b_1-b_2}\right)$, the increase of the potential market share of indirect channel will result in the direct channel profit flowing to the indirect channel.

5.2 Manufacturer decides on wholesale prices in subgame PG-D

In subgame PG-D, the manufacturer first determines the green degree of the product, the direct price, and the wholesale price for the indirect channel. Then the retailer

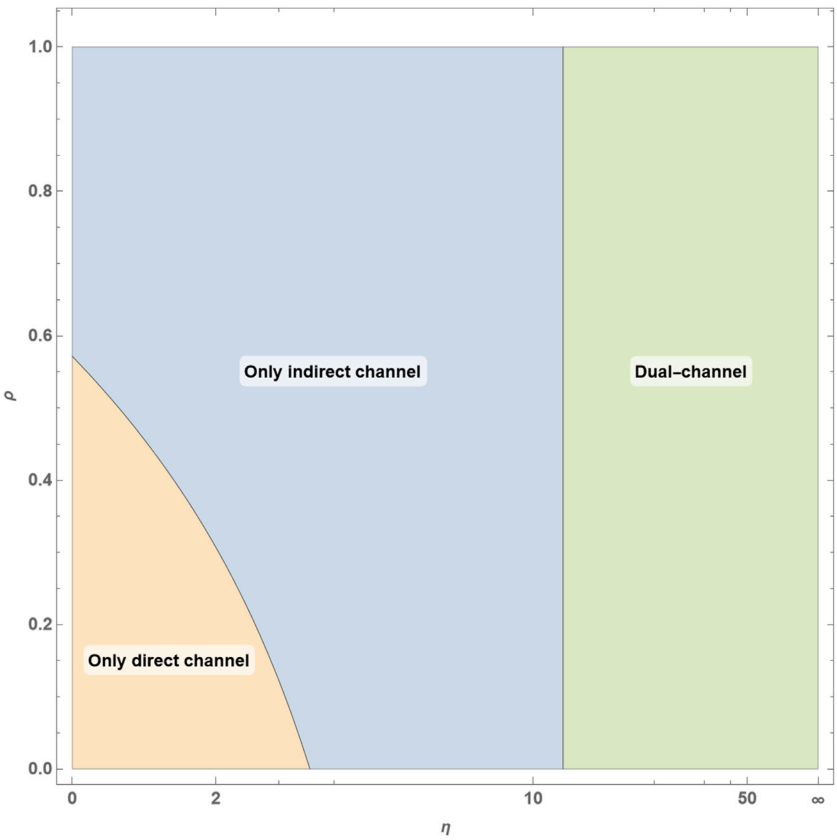

FIGURE 9
The outcomes of model extension of subgame PG-D, where $b_1 = 6$, $b_2 = 5$, $\beta_r = 4$, $\beta_m = 3$.

decides the indirect channel price. By employing the method of backward induction, we can derive the equilibrium solutions as described in Proposition 6.

Proposition 6. In subgame PG-D, we can obtain the equilibrium solutions as follows (the expression of $p_{m3}, p_{r3}, w_1, \eta_5$ and η_6 are shown in Supplementary Appendix):

(I) When (a) $0 < \rho < \frac{\beta_r}{\beta_m + \beta_r}, \eta_6 \le \eta \le \eta_5$ or (b) $\frac{\beta_r}{\beta_m + \beta_r} \le \rho < 1, 0 < \eta \le \eta_5$, the direct channel demand $D_m^d = 0$, the optimal indirect channel price, the optimal green degree and wholesale price are $p_r^d = \frac{3a\eta\rho}{4b_1\eta - \beta_r^2}$, $\theta^d = \frac{a\beta_r\rho}{4b_1\eta - \beta_r^2}$ and $w^d = \frac{2a\eta\rho}{4b_1\eta - \beta_r^2}$, respectively.

(II) When $0 < \rho < \frac{\beta_r}{\beta_m + \beta_r}, 0 < \eta < \eta_6$, the indirect channel demand $D_r^d = 0$, the optimal direct channel price and green degree are $p_m^d = \frac{a\eta(1-\rho)}{2b_1\eta - \beta_m^2}$, and $\theta^d = \frac{a\beta_m(1-\rho)}{2b_1\eta - \beta_m^2}$, respectively.

(III) When $0 < \rho < 1, \eta > \eta_5$, the optimal prices for the direct and indirect channels, the optimal green degree and wholesale price are $p_m^d = p_{m3}, p_r^d = p_{r3}, \theta^d = \theta_3$ and $w^d = w_1$, respectively.

The above result is shown in Figure 9.

Proposition 6 indicates that when the green cost coefficient η is high ($\eta > \eta_5$), the dual-channel strategy is the optimal channel strategy. When both the potential market share of the indirect channel ρ and the green cost coefficient η are low ($0 < \rho < \frac{\beta_r}{\beta_m + \beta_r}, 0 < \eta < \eta_6$), the manufacturer will introduce a direct channel to sell products. However, when the green cost coefficient η is moderate or the potential market share of the indirect channel ρ is high ($\eta_6 \le \eta \le \eta_5$ or $\rho \ge \frac{\beta_r}{\beta_m + \beta_r}$), a standalone direct channel cannot attract enough consumers, but the indirect channel can attract more consumers due to β_r is greater than β_m. In this case, the manufacturer only needs to set a reasonable wholesale price to obtain substantial profit to offset the green cost, without the need to introduce a direct channel. Then, we illustrate the effects of multiple parameters ($a, \rho, b_1, b_2, \beta_m, \beta_r$ and η) on the wholesale price, indirect channel price and profits in dual-channel in Figure 10.

Figure 10 illustrates that in subgame PG-D, the wholesale price (w) increases with the rise in potential market demand (a), the cross-price sensitivity coefficient (b_2), and consumers' environmental awareness in different channels (β_m and β_r). Concurrently, direct channel profit (π_m), indirect channel price and profit (p_r and π_r) also increase. Conversely, the wholesale price (w) decreases with the increase in marginal channel demand (b_1) and the cost coefficient per unit of green degree (η), leading to a decrease in direct channel profit (π_m), indirect channel price and profit (p_r and π_r). As the potential market share of indirect channel (ρ) increases, the wholesale price (w) and indirect channel price (p_r) increase slowly, while indirect channel profit (π_r) increases significantly and direct channel profit (π_m) decreases substantially. This is very similar to the conclusions of Corollary 3.

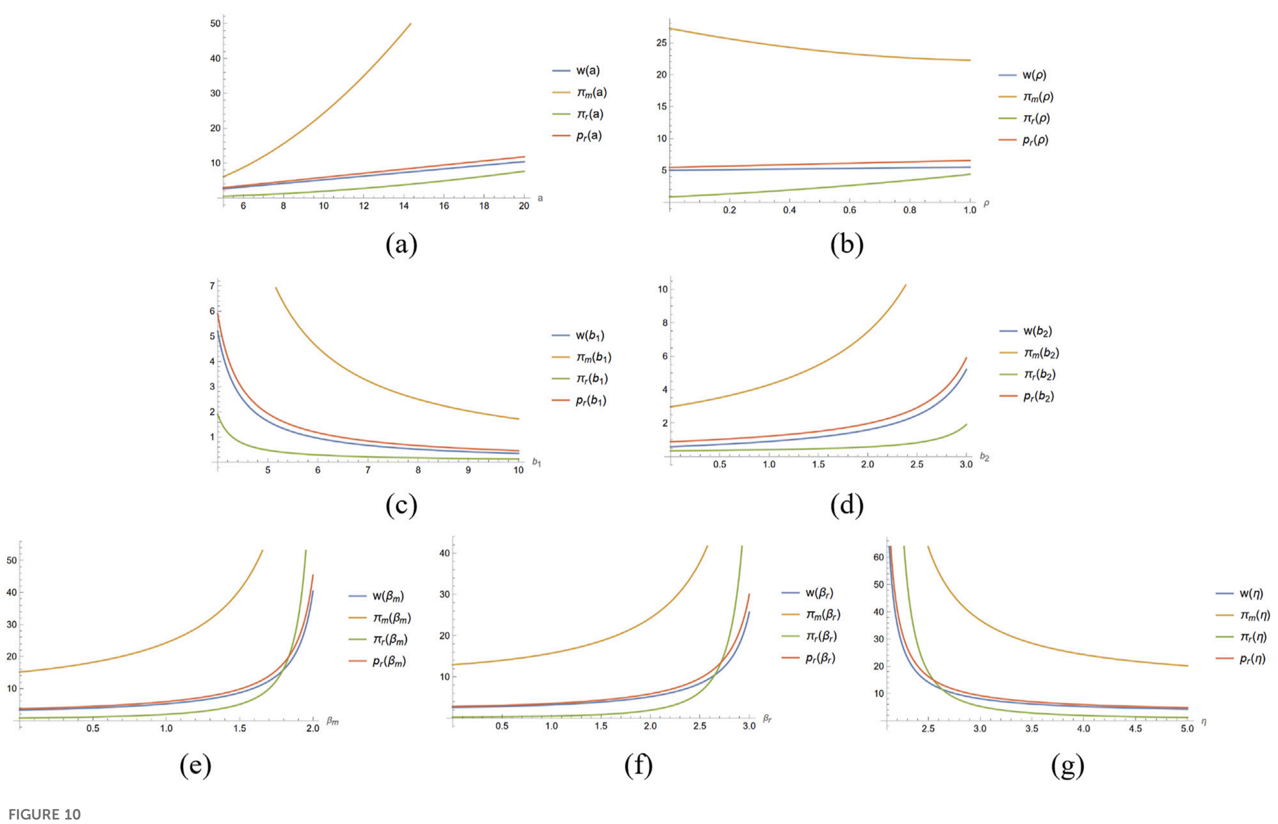

FIGURE 10
The impact of different coefficient on wholesale price w, direct channel profit π_m, indirect channel price p_r, and indirect channel profit π_r, where $a = 10$, $b_1 = 4$, $b_2 = 3$, $\beta_r = 2$, $\beta_m = 1$, $\rho = 0.4$, $\eta = 4$, $5 \le a \le 20$, $0 < \rho < 1$, $4 \le b_1 \le 10$, $0 \le b_2 \le 3$, $0 \le \beta_r \le 3$, $0 \le \beta_m \le 2$, $2.1 \le \eta \le 5$.

6 Conclusion

This paper proposes a dual-channel supply chain model to study the green degree and pricing strategies of manufacturers under centralized and decentralized decisions. We also analyze the strategic role of the wholesale price setting by the manufacturer to control the distribution channels of the product, and the impacts of the green degree decision on prices and profits of different channels. The results show that, dual channels will always be introduced under centralized decision-making; while dual channels will be introduced only when the wholesale price is relatively low under decentralized decision-making. When the green degree decision is involved, prices and profits in all scenarios and channels increase, with higher increases in prices and profits and a higher optimal green degree under centralized decision-making. When the potential market share of indirect channel increases, the manufacturer, who bears the green costs under decentralized decision-making, will reduce the green degree and price; while the manufacturer will continue to increase the green degree under centralized decision-making. Moreover, when potential market demand is low and the green cost coefficient is high, the manufacturer prefers a single direct channel strategy rather than a dual-channel strategy which would benefit all channels. As the green degree increases, the prices in all channels will increase under centralized decision-making; while the indirect channel price will decrease under decentralized decision-making. This indicates that, without the impact of double marginalization, channel members can better leverage the advantages brought by green degree; however, under decentralized decision-making, manufacturers often make decisions that are detrimental to the long-term development of the dual-channel in an effort to compensate for their own costs. Furthermore, the wholesale price can always be acted as a strategic tool for the manufacturer to control the distribution channels and guarantee total profits. Without the introduction of the green degree, the manufacturer always prefers dual-channel strategy. Once the green degree is introduced, the manufacturer tends to set a high wholesale price to "drive away" the indirect channel when the potential market share of the indirect channel and the green cost coefficient are both low; Otherwise, the manufacturer will depend on the indirect channel to guarantee the channel profits. At last, enhancing consumers' environmental awareness and updating technologies to reduce green costs will always benefit channel members. This approach will simultaneously increase the green degree, channel prices and profits, creating a positive cycle, especially under centralized decision-making. The limitations of this paper are as follows: we ignore other factors such as consumers' preferences for different channels, sales efforts, information asymmetry, etc. Also, we do not consider the cooperation between the manufacturer and the retailer to share the green costs.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

XL: Writing–original draft, Writing–review and editing. YW: Writing–review and editing. YZ: Writing–original draft. CL: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1463076/full#supplementary-material

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