International Journal of Innovative Computing, Information and Control
Volume **22**, Number **3**, June **2026**
ICIC International ©2026 ISSN 1349-4198
pp. **737–754**

RESEARCH ON DUAL-CHANNEL SUPPLY CHAIN DECISIONS UNDER CARBON CAP-AND-TRADE POLICY WITH CONSUMER LOW-CARBON PREFERENCES

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Received October 2025; revised February 2026

Abstract. *Global warming has become a critical constraint on global sustainable development, with manufacturing widely regarded as the core entity undertaking the "zero-carbon" mission. Amid accelerating green and low-carbon transformation, enterprises must simultaneously deploy emission reduction strategies at both production and channel levels while navigating the interplay among government regulations, consumer preferences, and carbon market mechanisms. To address this challenge, this study constructs a two-level supply chain game model comprising a manufacturer and a retailer, where consumers make product choices based on their low-carbon preferences. Employing game theory and comparative static analysis, this research examines how carbon quota, carbon trading prices, and consumers' green preferences influence manufacturers' carbon reduction and channel decisions. Our analysis reveals the following findings. First, dual-channel operations combined with emission reduction investments generate the highest profits for manufacturers by enabling broader market coverage and capturing the demand premium from low-carbon preferences. Second, retailers' profits also increase with carbon prices, quotas, or consumer preferences under both single and dual-channel emission reduction scenarios. Third, the emission reduction rate remains higher in the dual-channel model than in the single-channel model under identical conditions, amplifying incentives for low-carbon investment.*

Keywords: Dual-channel supply chain, Carbon trading policy, Emission reduction, Low carbon preference

1. Introduction.

Amid mounting environmental degradation and accelerating climate change, sustainable development has moved to the forefront of global concern. Riding the worldwide wave of carbon-neutrality pledges, carbon-trading policies have rapidly emerged as a core market-oriented mechanism for climate governance. By 2024, 75 distinct emissions-trading systems were in operation worldwide, collectively covering 24% of global greenhouse-gas emissions[1]. These mechanisms convert carbon into a quantifiable factor of production through the allocation and trading of allowances, effectively steering economic entities toward low-carbon development trajectories. China's national carbon market has also achieved tangible emission reduction effects: 180 million tons of allowances were

DOI: 10.24507/ijicic.22.03.737

[1]https://paper.people.com.cn/zgnyb/pc/content/202412/02/content_30033598.html (Accessed on 20 February, 2026)

traded in its first compliance cycle, driving a 4.3% reduction in per-ton steel emissions[2], which verifies the practical value of carbon trading policies in promoting industrial low-carbon transformation.

Simultaneously, the digital transformation of the retail industry has fundamentally reshaped the sales models of manufacturing enterprises. The integration of Internet technology, e-commerce platforms and modern logistics systems has made dual-channel supply chains – combining traditional offline retail and online direct sales – a mainstream strategic choice for manufacturers. Well-known enterprises such as HP, Apple and Nike have built multi-layered sales networks by adding e-commerce channels to their traditional retail systems, while once direct sales-only brands like Dell and Gateway have re-entered physical store channels. This dual-channel operation model helps enterprises capture broader consumer segments and improve market coverage efficiency, but the convergence of carbon-trading regimes and dual-channel operations has also brought new challenges to corporate decision-making, forcing manufacturers to re-examine and optimize their emission reduction and channel operation strategies in a coordinated manner.

The changes in consumers' purchasing psychology have further amplified the transformation of corporate decision-making logic. As environmental awareness takes root and enterprises promote low-carbon products via multi-channel marketing, consumers' focus on green product attributes has evolved into quantifiable purchasing preferences and actual behaviors. A 2024 PwC survey shows over 80% of consumers are willing to pay a 9.7% premium for eco-friendly products[3]. When low-carbon demands are closely linked to consumption, corporate emission reduction investment becomes not just a passive response to policy constraints, but an active strategic choice to capture market demand and gain competitive edges. This tightens the correlation between emission reduction investment and channel layout: manufacturers must boost low-carbon R&D and process optimization to cut emissions, while balancing environmental goals and operational efficiency in traditional and online channel deployment. Thus, exploring the joint emission reduction and pricing decisions of dual-channel supply chains under carbon cap-and-trade policies – considering consumer low-carbon preferences – carries important theoretical and practical significance for manufacturing's low-carbon transformation and supply chain sustainable development.

In the existing research on carbon cap-and-trade policies, scholars have focused on its theoretical connotation, micro-enterprise behavior impact and industrial structure adjustment effect. The theoretical roots of carbon trading can be traced back to the "negative externality correction" theory of environmental economics, with Coase's property rights theory and Pigou's "Pigou tax" laying its ideological foundation [1]. Zhou et al. found that the policy can effectively internalize the external costs of carbon emissions through market means and encourage enterprises to carry out voluntary emission reduction [2]. In practice, carbon trading policies have prompted micro-enterprises to re-examine their production and operation models under cost constraints: high-energy-consuming enterprises such as power generation and steel have incorporated carbon costs into their financial accounting systems, and reduced unit carbon emissions through technological R&D and process optimization to avoid the high cost of purchasing carbon quota [3-5]. From an industrial perspective, Raymond [6] and Zhang et al. [7] discovered that the price signals formed by carbon trading have guided the reallocation of production factors between high-carbon and low-carbon industries, accelerating the transfer of capital, technology and labor to

[2]https://www.cneeex.com/upload/resources/file/2022/04/29/28212.pdf (Accessed on 20 February, 2026)

[3]https://wallstreetcn.com/articles/3715215 (Accessed on 20 February, 2026)

new energy and other low-carbon industries, and driving the green transformation of the overall industrial structure.

Another stream of the research that is closely related to our study is dual-channel supply chain operations. Scholars have found that dual-channel operation can effectively alleviate the double marginalization of the supply chain, and the green cost-sharing contract and profit-sharing mechanism in the dual-channel model have a better coordination effect than the single-channel model – the sales efforts of retailers in traditional channels and the green image of online direct sales channels can complement each other, thereby expanding the market demand for green products [8,9]. In addition, Heydari et al. [10] and Ranjan and Jha [11] found that manufacturers can directly control the green image of products through online direct sales channels, obtain green price premiums from consumers, and thus have a stronger motivation to carry out green investment and emission reduction.

Against the backdrop of global climate change response, consumers' low-carbon preferences have become a key market factor driving the development of the low-carbon economy. Du et al. have defined consumer low-carbon preference as a preferential choice tendency for low-carbon products or services in consumption decisions [12], and Song et al. pointed out that concern for the carbon footprint of products is its core manifestation [13]. Li et al. revealed that such preference is jointly affected by internal and external factors: internal factors include consumers' environmental protection values, social responsibility and quality of life pursuit, while external factors involve market consumption culture, product functional attributes and environmental perception [14]. In terms of market impact, consumers' low-carbon preferences can significantly incentivize supply chains to carry out emission reduction investment, and enterprises can gain higher market share and profit levels by increasing R&D investment in low-carbon products to meet consumer demand [15]. At the industrial level, McCollum et al. believed that the rising low-carbon preferences of consumers have driven the low-carbon upgrade of traditional industries such as the automotive industry, prompting fuel vehicle enterprises to accelerate their layout in the new energy field [16].

Although the existing research has yielded fruitful results and formed a relatively complete theoretical system, obvious gaps remain in integrating the three core elements, which constitute the research motivation and innovation of this paper. First, most studies explore the impacts of carbon cap-and-trade policies on emission reduction or dual-channel green supply chain operations in isolation, rarely integrating carbon policy factors and dual-channel characteristics to study their joint decision-making, ignoring their synergistic interaction in low-carbon supply chains. Second, the effect of consumers' direct channel preference on emission reduction motivation is unclear, with insufficient quantitative analysis of its impact on supply chain emission reduction decisions and profit distribution. Third, research on carbon trading prices mostly focuses on single-channel scenarios, lacking in-depth discussion on their differential impacts on single and dual-channel supply chains, failing to provide targeted decision references for enterprises.

To fill these gaps, this study constructs a manufacturer-retailer dual-channel supply chain Stackelberg game model under carbon cap-and-trade policy. By analyzing the equilibrium results of three decision models, it examines core factors' impacts on manufacturers' emission reduction rates and channel pricing, and verifies conclusions via numerical simulation and sensitivity analysis. Our study's main contributions are threefold. First, we construct a unified Stackelberg game framework integrating carbon cap-and-trade policy, dual-channel supply chain structure and consumer low-carbon preferences, verifying dual-channel operations with emission reduction investment maximize manufacturers' profits via expanded market coverage and low-carbon demand premiums. Second, we quantify the interaction between channel preference, emission reduction incentives and profit distribution, proving retailers' profits rise with carbon prices, quotas and low-carbon preferences in both single and dual-channel emission reduction scenarios. Third, we compared the impact of different channel modes on emission reduction decisions, confirming higher optimal emission reduction rates in dual-channel models and their amplification effect on low-carbon investment incentives.

This paper is structured as follows. Section 2 elaborates on the problem description, model assumptions and variable definitions. Section 3 solves the three models' equilibrium results and conducts analysis and corollary derivation. Section 4 carries out key parameter sensitivity analysis via numerical simulation and discusses managerial implications. Finally, Section 5 summarizes conclusions, puts forward targeted suggestions and points out future research prospects.

2. **Model Description and Construction.**

2.1. **Problem description.** Considering a secondary supply chain composed of a manufacturer and a retailer, the manufacturer has two sales channels: retail and direct sales. For the retail channel, the manufacturer sells products to consumers via the retailer, while through the direct sales channel, the manufacturer sells products directly to consumers. And the manufacturer determines the wholesale price, and the retailer sets the retail price accordingly. In this process, manufacturers are subject to carbon emissions, and the government allocates corresponding free carbon quota to manufacturers based on their historical emission data in accordance with regulatory rules, and enterprises will buy or sell carbon emission rights from the carbon trading market according to actual needs.

The model's timing proceeds as follows:

Stage 1. The government sets the carbon emission quota.

Stage 2. The manufacturer sets wholesale price w and carbon emission reduction rate θ.

Stage 3. Retailers set retail price p based on wholesale price.

The overall framework of the model is shown in Figure 1.

2.2. **Model assumption.** To make the model in this study more in line with the actual situation and operational, the following hypotheses are proposed.

1) The carbon market offers free trading and sufficient carbon emission rights, allowing for trading at any time. And the trading price per unit of carbon remains stable within one production cycle.

2) Assuming that the consumer's demand function is linear, according to the study of Jamali and Rasti-Barzoki [17], the demand is influenced by price p, carbon emission reduction intensity θ and the consumer's direct sales channel preference μ.

3) To mitigate channel conflicts between different sales channels, we referred to the research of Li et al. [18] and assumed a uniform pricing strategy is implemented for both online and offline channels, with the retail price uniformly set by the retailer.

4) The manufacturer acquires a carbon emission quota of G within one production cycle. And we assume that the manufacturer's production cost is 0 to simplify the research model. If the manufacturer's carbon emissions do not exceed the prescribed quota G after consumption in this production cycle, the remaining carbon quota can be sold to other production enterprises at a price of k per ton through the carbon market to obtain carbon benefits. If the emissions exceed the carbon quota G, the corresponding carbon emission rights must be purchased through the carbon market at a price of k per ton.

5) The carbon emissions of products mainly occur during the production process. To reduce carbon emissions, manufacturers need to invest costs C in conducting research

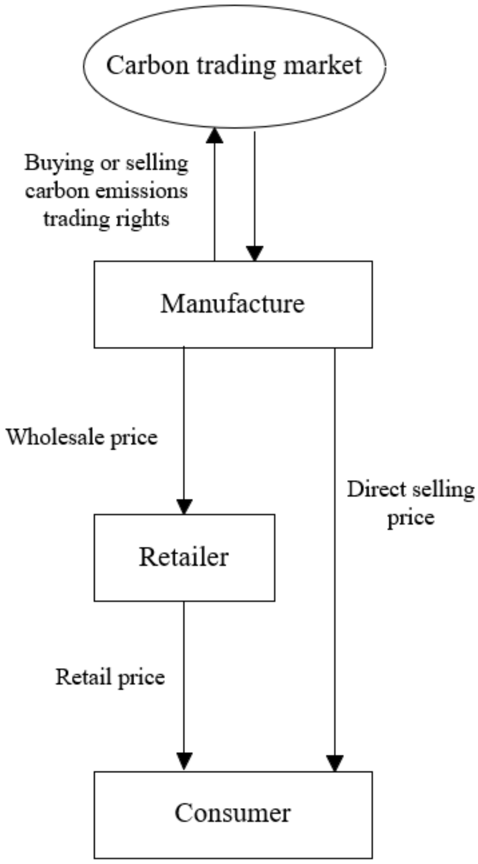

FIGURE 1. Dual-channel supply chain model under carbon trading policy

and development for energy conservation and emission reduction. Therefore, similar to Yang et al. [19], the investment cost of emission reduction C is a quadratic function of the increase in the reduction rate of carbon emissions per unit product θ, that is $C = \frac{1}{2}M\theta^2$, where M denotes carbon emission reduction cost coefficient.

For notational convenience, in subsequent analysis, subscripts r and m denote the retailer and the manufacturer, respectively. And superscripts s, d, and dn denote single-channel emission reduction model, dual-channel emission reduction model and dual-channel non-emission reduction model, respectively. Table 1 defines the decision variables and model parameters.

3. Model Analysis.

3.1. Model 1: Single channel decision-making for emission reduction.

In Model 1, each member of the supply chain takes maximizing their own profits as the decision-making goal. Manufacturers sell their products only through retail channels and choose to implement carbon reductions and invest in carbon reductions. The manufacturer first determines the wholesale price w^s and the carbon reduction rate θ^s, and the retailer determines the retail price p^s. Therefore, the inverse solution method is used to derive the equilibrium solution of the decision variable. Referring to the study of Dan et al. [20], the market demand function is as follows:

$$Q^s = a - p^s + \delta\theta^s \tag{1}$$

TABLE 1. Decision variables and model parameters

Notation	Description
Decision variables	
p	Retail price per unit of product
w	Wholesale price per unit of product
θ	Carbon emission reduction rate per unit of product
Model parameters	
δ	Low-carbon preferences of consumers
μ	Direct sales channel preferences of consumers
β	Price sensitivity of consumers
a	The amount of potential demand in the market
e	Initial carbon emissions per unit product
G	Carbon quota per unit product
M	Carbon emission reduction cost coefficient
k	Unit carbon trading price

The profit functions for manufacturers and retailers are

$$\begin{cases} \pi_m = w^s Q^s - k\left[e\left(1-\theta^s\right)-G\right]Q^s - \dfrac{1}{2}M{\theta^s}^2 \\ \pi_r = \left(p^s - w^s\right)Q^s \end{cases} \tag{2}$$

Proposition 3.1. *Under single channel decision-making for emission reduction, the equilibrium carbon reduction rate, retail price and wholesale price are shown in Table 2.*

TABLE 2. Equilibrium solution under Model 1

Notation	Equilibrium value
θ^s	$\frac{[(G-e)k+a](ek+\delta)}{4M-e^2k^2-2ek\delta-\delta^2}$
p^s	$\frac{[G\delta-e(a+\delta)]ek^2+\left[\left(-a\delta-\delta^2+M\right)e-\left(M-\delta^2\right)G\right]k+3aM}{4M-e^2k^2-2ek\delta-\delta^2}$
w^s	$\frac{[G\delta-e(a+\delta)]ek^2+\left[\left(-a\delta-\delta^2+2M\right)e-\left(2M-\delta^2\right)G\right]k+2aM}{4M-e^2k^2-2ek\delta-\delta^2}$

Corollary 3.1. *In Model 1, there is an optimal carbon emission reduction rate θ^s that maximizes the expected profit of manufacturers, and the optimal profits of both the manufacturer and the retailer increase with the intensity of consumers' low-carbon preference δ.*

Corollary 3.1 demonstrates that in a single-channel emission reduction decision model, manufacturers can identify an optimal carbon reduction rate that maximizes their expected profit. Furthermore, the optimal profits of both manufacturers and retailers increase with consumers' low-carbon preference intensity. This relationship operates through a closed-loop mechanism: stronger consumer preference amplifies the demand pull generated by each unit of emission reduction, thereby increasing marginal returns and incentivizing manufacturers to raise reduction rates until equilibrium is reached. Simultaneously, heightened low-carbon preference expands overall market size while mitigating the double marginalization within the supply chain. Consequently, the demand expansion effect brought by higher emission reduction rates offsets the price increase, thus mitigating the double marginalization of the supply chain. Although retailer profits are influenced by wholesale pricing strategies, they are ultimately dominated by this demand expansion effect. These findings reveal how consumer environmental awareness creates synergistic amplification effects, simultaneously strengthening emission reduction incentives and improving profit distribution across the supply chain.

Corollary 3.2. *In Model 1, carbon quota G and consumers' low-carbon preference δ have a positive impact on the carbon reduction rate θ^s.*

Corollary 3.2 demonstrates that in a single retail channel model incorporating carbon emission reduction investments, the carbon reduction rate is jointly influenced by several factors: consumer low-carbon preference and carbon quota exert a significant positive impact on the reduction rate, while the carbon reduction cost coefficient has a negative effect. Specifically, stronger consumer preference for low-carbon products and more generous government-allocated carbon quota incentivizes manufacturers to invest more in emission reduction technologies, thereby achieving higher reduction efficiency, whereas a rising emission reduction cost coefficient increases manufacturers' financial pressure and leads to a continuous decline in the reduction rate. This finding is supported by the practice of Caterpillar Inc., which operates primarily through third-party retail channels. As a regulated entity under carbon trading schemes, Caterpillar receives free carbon quota from regulatory authorities. Global demand for low-carbon construction equipment has been growing steadily, and most industrial clients are willing to pay a premium for eco-friendly products. Driven by this trend, the company has ramped up R&D investment in low-carbon power technologies, resulting in notable reductions in the unit carbon emissions of its core products. By aligning its product offerings with low-carbon market trends, Caterpillar has not only strengthened its market position in regions with strict carbon regulations but also generated additional revenue from selling surplus carbon allowances, further reinforcing its motivation to advance emission reduction technologies[4].

3.2. **Model 2: Dual-channel decision-making for non-emission reduction.** Under Model 2, manufacturers sell their products through dual channels and choose not to implement carbon reductions. So the manufacturer first determines the wholesale price w^{dn} of the product and the retailer determines the retail price p^{dn} of the product according to the wholesale price of the product and market demand. The market demand function is as follows:

$$\begin{cases} Q_m^{dn} = \mu a - \beta p^{dn} \\ Q_r^{dn} = (1-\mu)a - \beta p^{dn} \end{cases} \tag{3}$$

The profit functions for manufacturers and retailers are

$$\begin{cases} \pi_m^{dn} = p^{dn} Q_m^{dn} + w^{dn} Q_r^{dn} - \left[k(e-G)\left(Q_m^{dn} + Q_r^{dn}\right)\right] \\ \pi_r^{dn} = \left(p^{dn} - w^{dn}\right) Q_r^{dn} \end{cases} \tag{4}$$

Proposition 3.2. *Under dual-channel decision-making for non-emission reduction, the equilibrium retail price and wholesale price are shown in Table 3.*

Corollary 3.3. *The retail price p^{dn} is negatively correlated with consumers' direct sales channel preference μ, while the wholesale price w^{dn} is positively correlated with consumers' direct sales channel preference μ.*

[4]https://www.cat-cn.com/news/news-detail20250613.html (Accessed on 20 February, 2026)

Table 3. Equilibrium solution under Model 2

Notation	Equilibrium value
p^{dn}	$\frac{(3-2\mu)a-(G-e)2k\beta}{6\beta}$
w^{dn}	$\frac{\mu a-(G-e)2k\beta}{3\beta}$

Corollary 3.3 reveals that in a dual-channel decision-making model without emission reduction investments, consumer direct sales channel preference exerts divergent effects on pricing strategies. Specifically, the online direct price is positively correlated with consumers' preference for the online channel. The retail price in the traditional channel shows a negative correlation, while the wholesale price increases with the strength of direct sales channel preference. This theoretical finding is well illustrated by the dual-channel strategy of Mondelez International. Global consumers have increasingly favored online direct purchasing for daily snack products, driven by the convenience of home delivery and full product line access on brand official platforms. Benefiting from this trend, Mondelez International strategically raised the wholesale price for its offline third-party retail partners. Meanwhile, to maintain the viability and competitiveness of its offline retail network amid rising online channel penetration, offline retailers adjusted their terminal pricing strategy, lowering the uniform retail price for both channels to retain customer traffic. Stronger direct sales channel preference increases the manufacturer's channel bargaining power, enabling a higher wholesale price, while the rising wholesale price and online channel competition force the uniform terminal retail price downward to sustain offline market share[5].

3.3. **Model 3: Dual-channel decision-making for emission reduction.** Under Model 3, Manufacturers sell their products through dual channels and choose to implement carbon reductions. So the manufacturer first determines the wholesale price w^d of the product and the carbon emission reduction rate θ^d. And the retailer determines the retail price p^d of the product according to the wholesale price of the product and market demand. The market demand function is as follows:

$$\begin{cases} Q_m^d = \mu a - \beta p^d + \delta\theta^d \\ Q_r^d = (1-\mu)a - \beta p^d + \delta\theta^d \end{cases} \tag{5}$$

The profit functions for manufacturers and retailers are

$$\begin{cases} \pi_m^d = p^d Q_m^d + w^d Q_r^d - k\left[e\left(1-\theta^d\right) - G\right]\left(Q_m^d + Q_r^d\right) - \frac{1}{2}M\theta^{d^2} \\ \pi_r^d = \left(p^d - w^d\right)Q_r^d \end{cases} \tag{6}$$

Proposition 3.3. *Under dual-channel decision-making for emission reduction, the equilibrium carbon reduction rate, retail priceand wholesale price are shown in Table 4.*

Corollary 3.4. *In Model 3, there exists an optimal carbon emission reduction rate θ^d that enables manufacturers to achieve the maximum expected profit. Moreover, the carbon emission reduction rate θ^d is positively correlated with the carbon trading price k, carbon quota G, and consumers' low carbon preference δ.*

[5]https://www.mondelezinternational.com/investors/financials/annual-reports/ (Accessed on 20 February, 2026)

TABLE 4. Equilibrium solution under Model 3

Notation	Equilibrium value
θ^d	$\frac{2(ek\beta+\delta)[(G-e)k\beta+\mu a]}{(3M-4ek\delta)\beta-2e^2k^2\beta^2-2\delta^2}$
p^d	$\frac{[2G\delta-(a+2\delta)e]2ek^2\beta^2+[(G-e)2\delta^2+(\mu-1)2ae\delta+(e-G)M\beta]2k\beta+[(3-2a)M\beta+(2\mu-1)2\delta^2]a}{(3M-4ek\delta)2\beta^2-4e^2k^2\beta^3-4\delta^2\beta}$
w^d	$\frac{2[G\delta-(a\mu+\delta)e]ek^2\beta+\{2[G\delta-(\delta+\mu a)e]-(G-e)2M\beta\}k+aM\mu}{(3M-4ek\delta)\beta-2e^2k^2\beta^2-2\delta^2}$

Corollary 3.4 reveals the core driving mechanism behind the optimal carbon emission reduction rate for manufacturers within the dual-channel emission reduction model. Specifically, there exists a distinct optimal carbon emission reduction rate that maximizes manufacturers' expected profits, and this rate exhibits a significant positive correlation with carbon quota trading prices, government-allocated carbon quota, and consumers' low-carbon preferences. These three factors jointly impel manufacturers to scale up emission reduction investments through the dual pathways of cost constraint and market demand, thereby validating the synergistic incentive effect of carbon policy regulation and market demand preferences on enterprises' low-carbon decision-making. Theoretically, a hike in carbon quota trading prices pushes up the opportunity cost of corporate carbon emissions: the gains from selling surplus quotas and the costs of purchasing additional ones for over-emission both compel enterprises to optimize carbon asset returns through emission reduction. Rational government allocation of carbon quota provides a policy buffer and operational leeway for corporate emission reduction efforts, with abundant quotas incentivizing enterprises to monetize excess quotas via proactive emission reduction. Meanwhile, the growing prevalence of consumers' low-carbon preferences directly translates into a market demand premium for low-carbon products, allowing enterprises to convert emission reduction investments into tangible profits through higher sales volumes and product pricing. Collectively, these three factors form a combined policy-and-market incentive, driving the optimal emission reduction rate to a higher level.

In practice, the development of China's steel industry has empirically confirmed this conclusion. As a core sector covered by China's national carbon market, steel enterprises are assigned uniformly approved carbon quota by the government. In 2024, the carbon trading price in China's national carbon market surged by over 60% compared with its initial launch in 2021. Against this backdrop, downstream manufacturing industries have shown a steadily rising preference for low-carbon steel products. Leveraging this trend, China Baowu Steel Group has increased R&D investment in low-carbon smelting technologies, raising its carbon utilization rate from the industry average of 45% to 72%. In addition, the group has cut carbon emissions by more than 60% compared with traditional production processes and reduced the cost per ton of iron by approximately 150 yuan, reaping substantial economic benefits[6]. The formulation of Baowu Steel Group's optimal emission reduction rate is precisely the outcome of the combined effects of carbon prices, government carbon quota, and market low-carbon preferences.

Corollary 3.4 also offers theoretical underpinnings for the two-way decision-making of both enterprises and the government. For manufacturers, it is imperative to integrate policy changes in carbon prices and carbon quota, as well as market trends in consumers' low-carbon preferences, into their emission reduction decision-making systems, and dynamically adjust emission reduction investments to align with the optimal emission reduction rate. For the government, it can forge a synergy between policy and market

[6]https://news.cnr.cn/native/gd/20251225/t20251225_527472726.shtml (Accessed on 20 February, 2026)

by appropriately regulating carbon trading prices, scientifically allocating carbon quota, and guiding low-carbon consumption in the market. This approach drives enterprises to achieve low-carbon transformation while maximizing profits, thereby turning carbon emission reduction from a corporate cost burden into a robust profit growth driver.

4. Numerical Simulation and Sensitive Analysis.

To intuitively display the conclusions of our work, we conduct numerical simulations using Matlab. Based on the existing literature [21,22] and industrial practice, the parameters used are as follows. Consumer direct-channel preference $\mu = 0.7$ reflects high direct sales acceptance under e-commerce development. Low-carbon preference $\delta = 0.5$ indicates moderate green awareness without over-optimism. Carbon trading price $k = 0.4$, initial emissions $e = 11$, and carbon quota $G = 10$ are set in line with early trading price range of China's national carbon market (around 40-60 yuan/ton) and typical quota levels for manufacturing firms. Standardized for model consistency, they represent reasonable emission reduction pressure while allowing manufacturers to gain returns from carbon abatement. Emission reduction cost coefficient $M = 100$ characterizes the high cost of deep decarbonization in the manufacturing industry. Market size $a = 20$ and price sensitivity $\beta = 0.6$ follow the classic settings of Benjaafar et al. [22] to ensure stable equilibrium solutions. Taking carbon trading price, carbon quota and consumer low-carbon preference as independent variables, respectively, the magnitude and change trend of other factors in the supply chain are observed.

4.1. How do carbon trading price, carbon quota, low-carbon preferences affect profits of manufacture?

Figure 2 shows that the impact of carbon trading price fluctuations on manufacturers' profits varies greatly depending on their emission reduction strategies. When manufacturers choose not to invest in carbon emission reduction, their profits show a downward trend as the carbon trading price rises. This is because firms without emission reduction investments have to pay higher costs for excess carbon emissions and cannot obtain carbon asset gains through emission reduction activities, and the price increase directly exacerbates cost pressure. In contrast, when manufacturers choose to invest in carbon emission reduction, their profits show a continuous upward trend as the

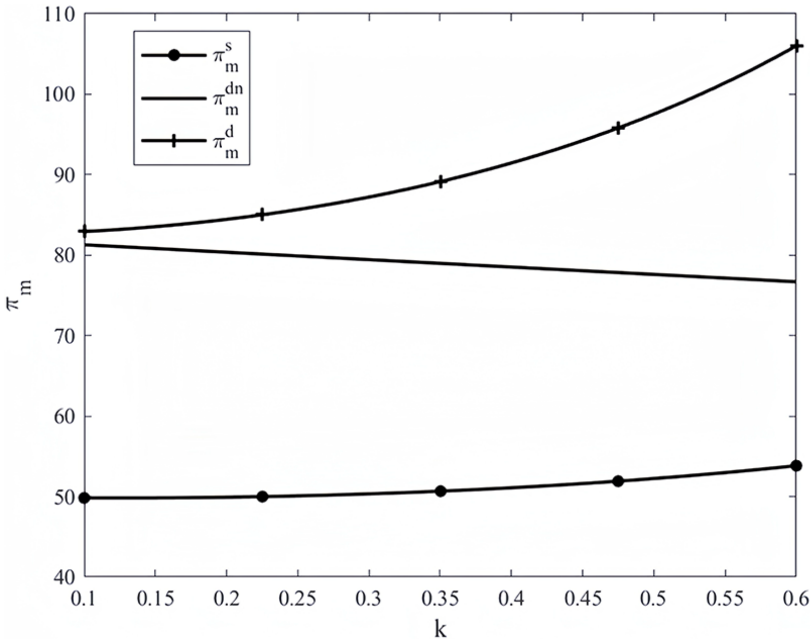

FIGURE 2. The impact of carbon trading price on manufacturers' profits

carbon trading price rises. In this case, firms can not only reduce carbon emission cost, but also obtain additional income by selling surplus carbon quota, thus forming a dual positive effect of cost savings and revenue growth. Notably, under the premise that manufacturers choose to make emission reduction investments, a comparison of different channel models shows that manufacturers' profits grow more rapidly under the dual-channel model. This is attributed to the fact that the dual-channel structure expands market coverage and further amplify the revenue advantages brought by emission reduction.

Figure 3 shows that the increase of carbon quota has a positive impact on manufacturers' profits. As carbon quota increases, firms gain greater flexibility in carbon emission management, which lowers the cost risk of excessive emissions and enables them to obtain quota benefits via emission reduction, thus improving profitability. Further analysis of the joint effects of channel structures and emission reduction strategies indicates that manufacturers achieve the highest profit under the dual-channel model combined with carbon emission reduction investment. This optimal combination fully exerts dual advantages: the dual-channel structure expands market coverage, while emission reduction investment amplifies the profit-enhancing effect of increased carbon quota by cutting carbon costs and raising the environmental value of products.

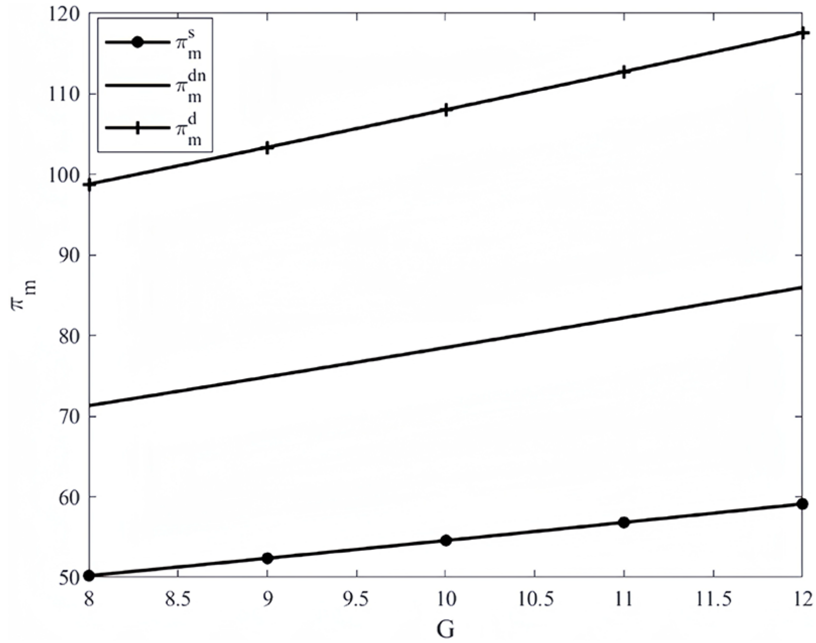

FIGURE 3. The impact of carbon quota on manufacturers' profits

As shown in Figure 4, as consumer low-carbon preference rises, manufacturer profit under the dual-channel emission reduction scenario increases significantly, while profit under the single-channel emission reduction scenario grows slowly, and profit under the dual-channel non-emission reduction scenario remains unchanged. This is because the dual-channel emission reduction scenario fully captures demand expansion and carbon quota benefits from low-carbon preference. In contrast, the dual-channel non-emission reduction scenario cannot obtain low-carbon premiums, and the single-channel emission reduction scenario is limited by coverage, leading to weak profit growth. The results confirm that dual-channel emission reduction is the optimal strategy for manufacturers to maximize profit under increasing consumer low-carbon preference.

4.2. **How does carbon trading price, carbon quota, low-carbon preferences affect profit of retailer?** As shown in Figure 5, as the carbon trading price increases,

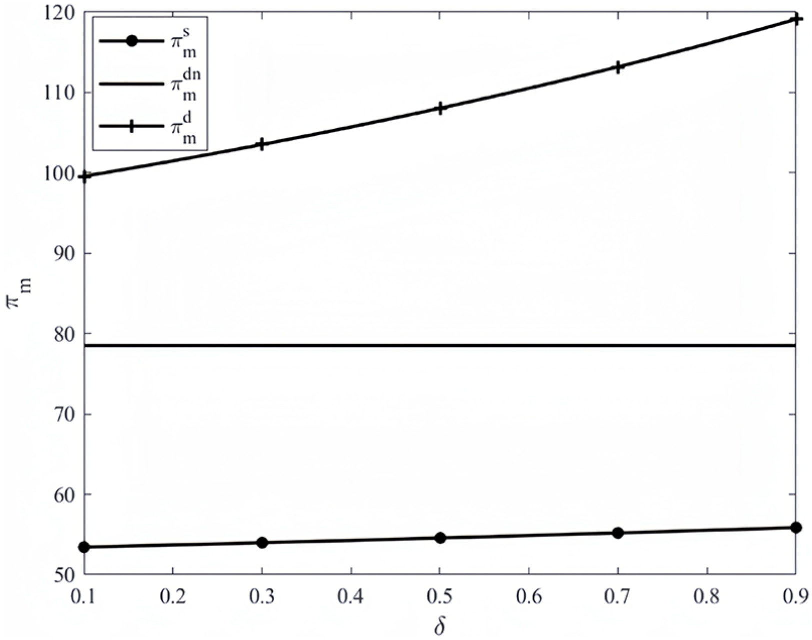

FIGURE 4. The impact of consumers' low-carbon preference on manufacturers' profits

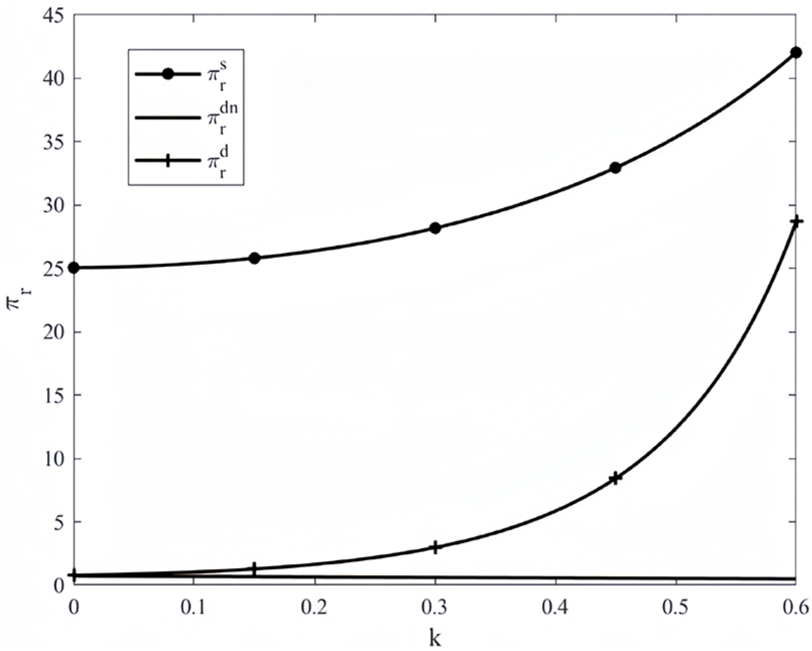

FIGURE 5. The impact of carbon trading price on retailers' profits

retailer profit under the single-channel emission reduction scenario rises steadily, while profit under the dual-channel emission reduction scenario grows sharply, and profit under the dual-channel non-emission reduction scenario slightly declines. This is because higher carbon prices incentivize manufacturers in emission reduction scenarios to cut emissions, boosting low-carbon product demand and passing on gains to retailers. In the dual-channel non-emission reduction scenario, manufacturers face higher carbon costs without emission reduction benefits, so they pass these costs to retailers through higher wholesale prices or reduced order quantities, leading to a slight profit decline. The results confirm that emission reduction scenarios are more beneficial to retailers under rising carbon prices.

Figure 6 reveals that, as the carbon quota increases, retailer profit under the single-channel emission reduction scenario rises steadily, while profit under the dual-channel emission reduction scenario grows moderately, and profit under the dual-channel non-emission reduction scenario remains nearly flat. This is because higher carbon quota reduce manufacturers' carbon cost pressure in emission reduction scenarios, allowing them to invest more in emission reduction and expand low-carbon product demand, which in turn increases retailers' sales volume and profit. In the dual-channel non-emission reduction scenario, manufacturers do not reduce emissions, so higher quotas only slightly reduce their carbon costs without driving demand growth, resulting in a slight increase in retailers' profits.

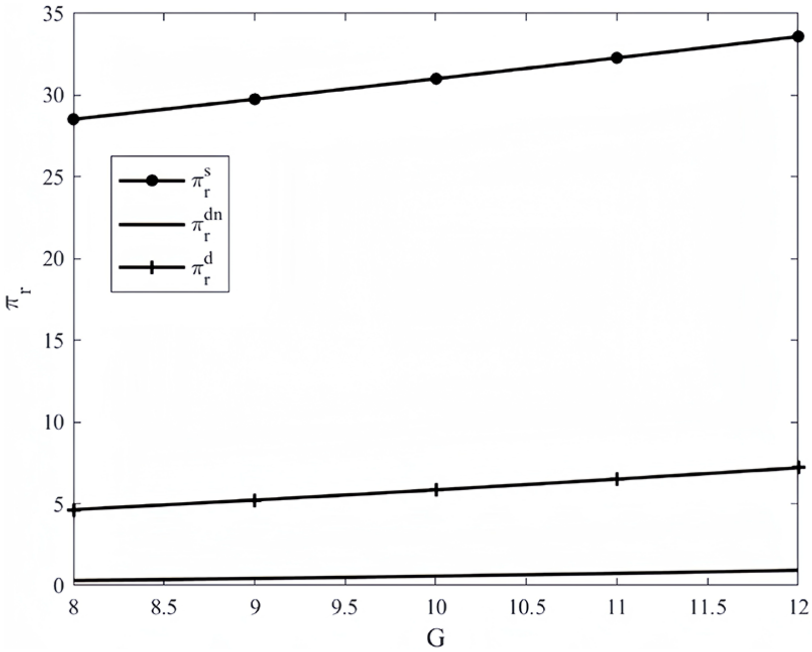

Figure 6. The impact of carbon quota on retailers' profits

According to Figure 7, we can find that as consumer low-carbon preference increases, retailer profit under the single-channel emission reduction scenario rises steadily, while profit under the dual-channel emission reduction scenario grows moderately, and profit under the dual-channel non-emission reduction scenario remains nearly flat. This is because stronger low-carbon preference boosts demand for low-carbon products, and in emission reduction scenarios, manufacturers increase emission reduction to meet this demand, expanding sales volume and benefiting retailers. In the single-channel emission reduction scenario, retailers capture most of this demand growth, leading to faster profit growth. In contrast, the dual-channel non-emission reduction scenario cannot leverage low-carbon preference to expand demand, so retailer profit stays stable.

4.3. **How does carbon trading price, carbon quota, low-carbon preferences affect carbon reduction rate?** As shown in Figures 8-10, the manufacturer's carbon emission reduction rate in the dual-channel emission reduction scenario is consistently higher than that in the single-channel emission reduction scenario, and both increase with rising carbon trading price, carbon quota, and consumer low-carbon preference. This is because the dual-channel structure expands market coverage and demand for low-carbon products, allowing manufacturers to offset higher emission reduction costs through increased sales volume and carbon quota gains, thus incentivizing a higher emission reduction rate. In contrast, the single-channel scenario limits demand growth, which weakens

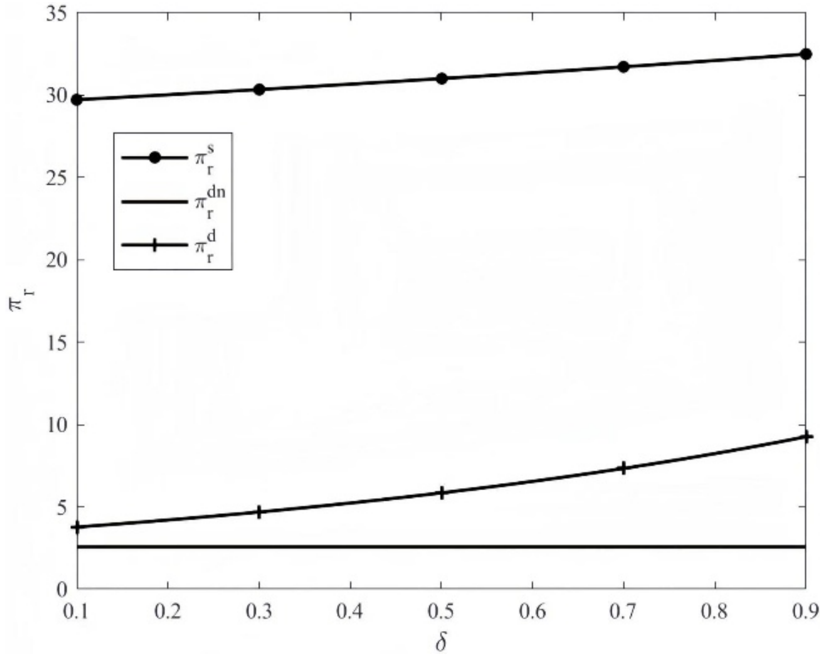

Figure 7. The impact of consumers' low-carbon preference on retailers' profits

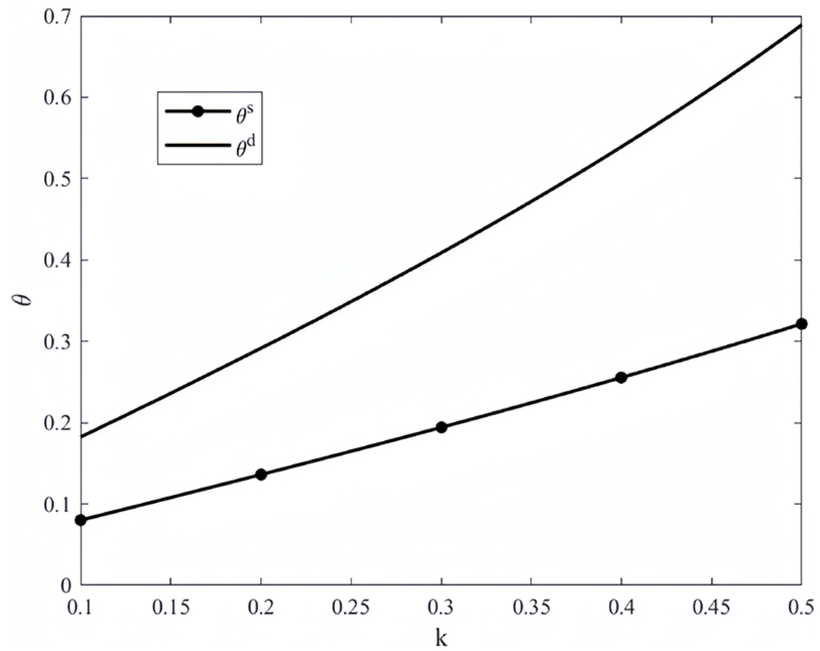

Figure 8. The impact of carbon trading price on the carbon reduction rate

the incentive for manufacturers to invest in emission reduction, as the benefits of lower emissions cannot be fully realized through limited sales channels.

Specifically, a higher carbon trading price increases the opportunity cost of carbon emissions, making emission reduction more profitable for manufacturers in both scenarios by increasing the value of surplus quotas. A larger carbon quota provides manufacturers with more flexibility to monetize surplus quotas through emission reduction, further boosting their willingness to cut emissions and invest in low-carbon technologies. Stronger consumer low-carbon preference directly increases demand for low-carbon products, enabling

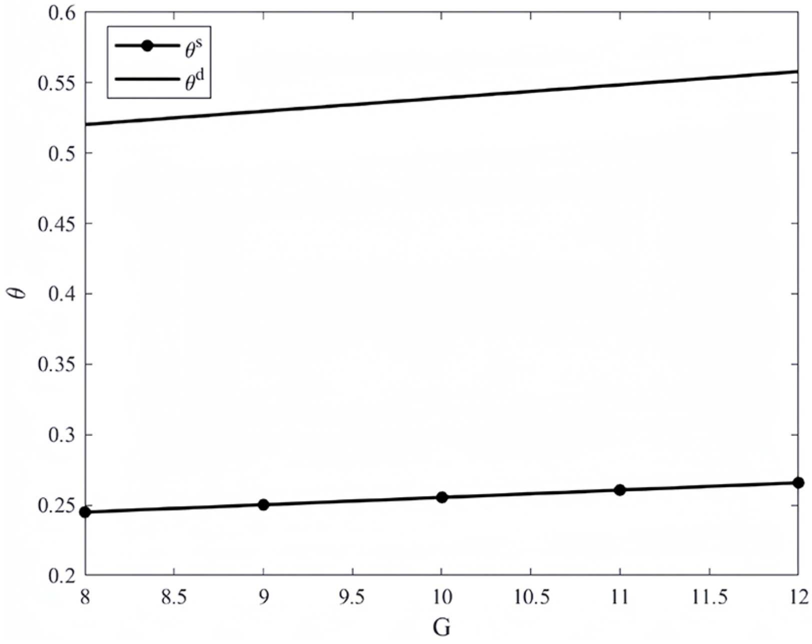

FIGURE 9. The impact of carbon quota on the carbon reduction rate

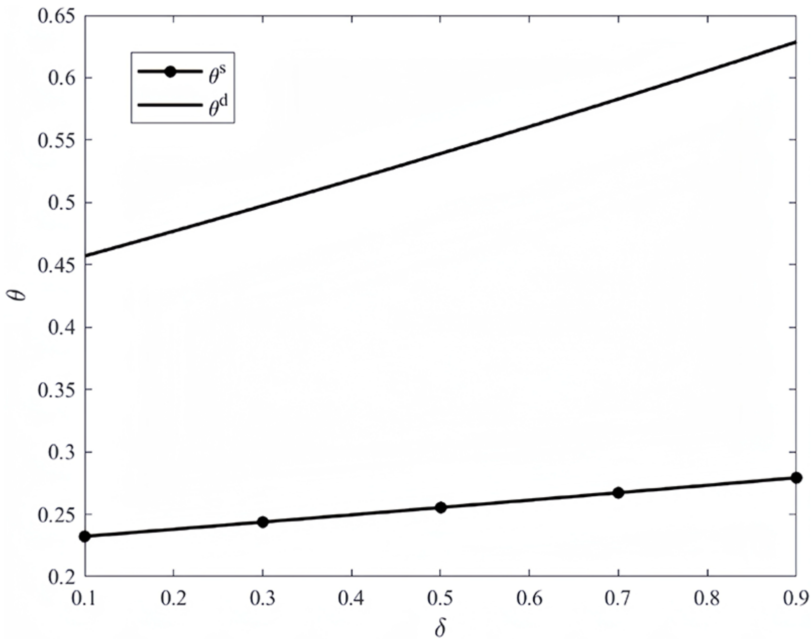

FIGURE 10. The impact of consumers' low-carbon preference on the carbon reduction rate

manufacturers to pass on emission reduction costs and gain higher profits through premium pricing, which in turn drives a higher emission reduction rate. Across all three factors, the dual-channel scenario consistently yields a stronger emission reduction incentive due to its expanded market reach and profit potential.

5. **Conclusion and Prospect.** This study develops a game-theoretic model to examine the joint emission reduction and pricing decisions of a dual-channel supply chain under carbon cap-and-trade policy, incorporating consumers' low-carbon preferences. By comparing three decision scenarios: single channel with emission reduction, dual-channel

without emission reduction, and dual-channel with emission reduction, the analysis reveals several key findings. First, dual-channel operation combined with emission reduction investment consistently yields the highest profits for manufacturers, as it enables broader market coverage and captures the demand premium generated by low-carbon preferences. Second, retailers also benefit from manufacturers' emission reduction efforts, with profits increasing under both single and dual-channel emission reduction scenarios as carbon prices, quotas, or consumer preferences rise. Third, the emission reduction rate is always higher in the dual-channel model than in the single-channel model under the same policy and market conditions, indicating that dual-channel structures amplify the incentive for low-carbon investment.

Based on the above conclusions, we propose the following suggestions.

For enterprises, the findings underscore the strategic value of integrating emission reduction investments with dual-channel operations. Manufacturers should actively expand online direct sales channels while investing in low-carbon technologies to capture the green consumption premium and maximize profits. The synergistic effect of dual-channel structure and emission reduction not only boosts manufacturer profitability but also benefits retailers. Moreover, firms must dynamically monitor carbon trading prices and shifts in consumer low-carbon preferences to adjust emission reduction rates and pricing strategies, transforming carbon assets into sustainable competitive advantages.

For policymakers, the results highlight the importance of coordinating carbon pricing, quota allocation, and demand-side interventions to amplify corporate emission reduction incentives. Appropriately raising carbon trading prices and allocating carbon quota scientifically can enhance the economic viability of low-carbon investments. Simultaneously, policies that enhance consumers' environmental awareness (such as carbon labels or green subsidies) can increase the market appeal of low-carbon products and amplify the effect of carbon reduction. Given that dual-channel supply chains exhibit stronger emission reduction responses, differentiated policy support (e.g., preferential quotas or green credit) for firms adopting both multi-channel strategies and active decarbonization could magnify the overall effectiveness of climate policies and accelerate economy-wide low-carbon transition.

Based on these findings, future research could extend the model to competitive supply chain settings, incorporate dynamic carbon prices or stochastic consumer preferences, and explore coordination mechanisms such as cost-sharing contracts. Comparative studies between carbon cap-and-trade and carbon tax policies under dual-channel structures also warrant further investigation.

Acknowledgement. This research was supported by the Chongqing Social Science Planning Funding (Grant/Award Number: 2024NDYB077).

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