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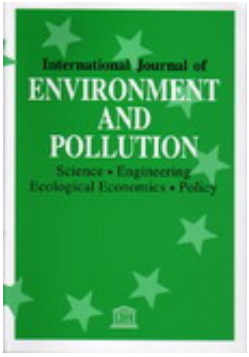

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Carbon reduction coordination and pricing strategy of a four-level supply chain under demand uncertainty

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Abstract: This study centres on how demand uncertainty impacts emission reduction in supply chains, premised on the Stackelberg game model. It delves into the collaborative emission reduction and pricing strategies of a four-echelon supply chain, including suppliers, producers, retailers and consumers, and meticulously examines the function of producers' carbon emission reduction subsidies and low-carbon product promotion subsidies in this process. The findings indicate that producers' reduction subsidies to suppliers and promotion subsidies to retailers play a coordinating role in supply chain emission reduction and product pricing, either directly or indirectly. The promotion subsidy for products with lower carbon emissions strengthens retailers' efforts to promote them and increases retail prices. Although these subsidies might lower producers' emission reduction levels and raise wholesale prices, they enhance the entire supply chain system's emission reduction.

Keywords: four-level supply chain; mission reduction subsidies; promotion subsidies; collaborative emission reduction.

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1 Introduction

A low-carbon economy represents an overriding trend for future global economic development, and as a result, future competition will centre on carbon productivity. Due to the gradual global consensus regarding 'green upgrading of supply chains' and 'collaborative carbon reduction in supply chains', these practices have been widely implemented. In 2020, the Chinese government introduced 'dual-carbon' goals (carbon peak and carbon neutrality), which impose more stringent requirements with respect to the green transition of China's economic development (Shao et al., 2022). Spurred by the rise of consumer awareness towards low-carbon initiatives and the implementation of carbon tax policies, a growing number of enterprises have initiated 'green production' and 'low-carbon production' strategies, actions that represent a significant step towards accelerating the transformation of production modes in the direction of sustainability and a reduction in carbon emissions across the entire production chain, i.e., from the generation of raw materials to product processing and marketing (Zhi et al., 2019; Hu and Li, 2024). Against this backdrop, how to promote collaborative carbon reduction in supply chains has emerged as a focal point of shared concern in both social practice and academic research.

Although the reduction of corporate carbon emissions has received widespread societal attention, extant research concentrates predominantly on energy consumption during production and transportation – typically measured as water or electricity use per unit product – while devoting comparatively limited attention to consumer awareness of low-carbon products. Leading e-commerce platforms (e.g., JD.com and Tmall), however, routinely label low-carbon products, simultaneously enhancing the market visibility of emission-reducing firms and increasing consumer salience of low-carbon attributes. Additionally, point-of-sale promotion facilitates direct interaction between retailers and consumers, thereby shaping consumer preferences. Consequently, although retailers are not directly involved in manufacturing, their actions critically influence the emission-reduction incentives of individual firms as well as entire supply chains.

Motivated by these observations, this study integrates retailers – hereafter referred to as the sales terminal – into a supply chain emission reduction framework. By explicitly incorporating

i the intensity of retailer promotion for low-carbon products

ii the retail price of such products and by accounting for consumer sensitivity to both carbon-reduction attributes and price,

we investigate how demand uncertainty affects the emission-reduction incentives of all supply chain actors and the overall effectiveness of coordinated abatement from raw-material production through processing to final sales.

Model analysis complemented by numerical simulation reveals that both the intensity of retailer promotion and the retail price of low-carbon products directly affect the profits of each supply chain node, thereby indirectly influencing the efficiency of coordinated emission reduction. For products characterised by comparatively low-carbon intensities, promotional subsidies strengthen retailer promotion efforts and increase retail prices. Although these subsidies may marginally diminish manufacturers' intrinsic motivation to

reduce emissions and raise wholesale prices, they also enhance the aggregate emission reduction level of the entire supply chain system. Moreover, the efficiency of coordinated abatement across all nodes directly feeds back into the promotion intensity and pricing decisions of the retailers.

This study contributes to the literature on supply chain coordinated emission reduction in three principal ways. First, relative to extant works that often focus on individual firms or isolated segments of the production chain, we explicitly incorporate demand uncertainty for low-carbon products and integrate retailer promotion intensity and retail pricing into a holistic supply-chain emission-reduction model, thereby broadening the analytical scope of coordinated abatement research. Second, our modelling framework simultaneously captures

a the influence of manufacturer-financed carbon-reduction subsidies on both the firm's processing activities and the upstream suppliers' raw-material emission-reduction efficiency

b the effect of these subsidies on retailer promotion intensity and retail pricing.

Third, the framework examines how retailer promotion and pricing decisions affect consumer demand and analyses the sensitivity of retailer behaviour to emission-reduction efficiency at the processing and raw-material stages. Taken together, the analytical results and numerical simulations demonstrate that effective supply chain coordinated emission reduction requires not only alignment among production and processing nodes but also explicit consideration of retail-terminal behaviour and its impact on consumer choice, thereby providing actionable insights for enhancing overall abatement efficiency.

2 Literature review

2.1 Longitudinal extension of the research object: from a dyadic chain to an ecological network

Early literature conceptualised the supply chain as a simple two-tier structure composed of 'suppliers and manufacturers' and treated profit maximisation as the sole objective. Hence, collaborative emission reduction emerged only as an endogenous decision variable (Yang and Yu, 2016). In reality, however, supply chain structural heterogeneity implies that profit-driven motives cannot fully explain the willingness to cooperate (Yu et al., 2020). During the past two years, the research focus has shifted markedly. Specifically, system profit has been reconceptualised as a mediating variable, scholars have begun to examine the emission-reduction behaviours of individual nodes, and consumer low-carbon preferences internalise the externality of emission reduction through demand elasticity, thereby effectively stimulating corporate abatement efforts (Xu et al., 2023; Zhou et al., 2024; Taleizadeh et al., 2025). Although consumer environmental awareness (CEA) exerts a stronger influence on manufacturers' carbon-reduction sensitivity than on the sensitivity of low-carbon product promotion (CSSLP) (Peng et al., 2024), rapid increases in abatement costs have increased product prices and suppressed demand, thereby generating a 'green-premium' bottleneck (Chang, 2023).

Consequently, several scholars have placed technological spillovers and carbon leakage into a unified framework. Whereas one strand proposes that information technology-driven knowledge-resource spillovers can reduce upstream–downstream information asymmetry and improve chain-wide emission-reduction efficiency (Yang et al., 2024), another strand investigates the impact of technological spillovers on supply-chain abatement performance and reveals the role of microlevel interactions in shaping macrolevel emission-reduction trajectories (Jiang et al., 2024). Thus, the research object of supply chain collaborative emission reduction has expanded from a 'chain' to a 'network', and abatement efficiency has become the core variable explaining the success or failure of collaboration.

2.2 Three-dimensional perspective: interactive coupling between external policy and internal governance

Carbon taxation, carbon trading, and carbon responsibility allocation constitute the policy toolbox. Accordingly, an increase in the carbon tax rate increases retail prices and suppresses demand, while the marginal incentive for abatement investment diminishes (Yang and Yu, 2016). Under a stringent cap-and-trade mechanism, a stable equilibrium is reached only when suppliers and manufacturers either simultaneously purchase or simultaneously forgo carbon allowances, i.e., governments must impose escalating penalties in the high-cost allowance interval to maintain collaborative incentives (Hu and Li, 2024). However, bidirectional option trading between suppliers and manufacturers can smooth price fluctuations and enhance the stability of collaborative emission reduction (Ghosh, 2022; Wang and Su, 2025). With respect to allowance allocation, when the government reduces the free carbon-emission quota, manufacturers tend to purchase additional allowances rather than invest in emission-reduction technologies (Li et al., 2025). Compared with grandfathering, benchmarking more effectively incentivises long-term abatement efforts (Xie et al., 2024). Collectively, these studies demonstrate that policy design must balance price-signal strength and expectation stability to drive interfirm collaboration effectively.

Consumer preferences, corporate social responsibility (CSR), and coordination contracts are regarded as the three principal internal levers of supply chain collaborative emission reduction. The being said, consumer low-carbon preferences internalise the abatement externality through demand elasticity (Peng et al., 2024). Specifically, when manufacturers assume CSR, the sensitivity of the optimal abatement rate to market size declines significantly, indicating that CSR can mitigate demand-fluctuation disturbances and create a 'market–responsibility' synergy that encourages manufacturers to raise the optimal abatement rate (Zhou et al., 2024). When the triple bottom line – economic, social, and environmental – is incorporated into the decision framework, system profit and abatement volume reach their maxima simultaneously when retailers bear CSR. Thus, internalised CSR can partially substitute for policy incentives (Ma and Lu, 2024). Among coordination contracts, existing studies consistently confirm that the revenue-sharing contract outperforms the cost-sharing contract in improving the system-wide abatement level, profits, and green promotion (Peng et al., 2024). For example, under a revenue-sharing contract, simultaneous improvements in product freshness and emission-reduction levels in fresh-food cold chains can be achieved even when the carbon-trading

price increases, thereby demonstrating the complementary effect between revenue sharing and policy incentives (Liu et al., 2024; Wang and Su, 2025). Nevertheless, other studies have concluded that the combined use of abatement subsidies and cost-sharing contracts can neutralise the crowding-out effect exerted by powerful firms on weaker partners, thereby stabilising collaborative emission reduction. This finding highlights the stability advantage of cost-sharing contracts in sustaining collaborative behaviour (Bao et al., 2024).

2.3 Paradigmatic shift in research methods: from static games to dynamic–evolutionary coupling

The Stackelberg game model is widely employed because it clearly captures leader–follower power structures (Zhi et al., 2019; Sun and Zhong, 2023; Zhou et al., 2024). A limited number of studies introduce quantum games (Chang, 2023) or differential games (Tan et al., 2023; Yang and Zhang, 2023) to capture long-term dynamics and the accumulation of advertising goodwill. For instance, Zhou and Ye (2018) employ a differential game to compare cooperative advertising and cost-sharing contracts and find that the former yields a more robust monotonic improvement in the abatement trajectory over the long term. Evolutionary game models possess unique advantages in depicting cooperative pathways and long-term trends, as they reveal how initial conditions, external policies, and internal contracts influence the evolutionary path and the final state of collaborative emission reduction. For example, Zhi et al. (2019) and Hu and Li (2024) adopt evolutionary games to depict the strategic evolution of suppliers and manufacturers in carbon-allowance purchasing and abatement cooperation and conclude that the direction of system convergence depends on initial states, cost–benefit structures and the intensity of government rewards and penalties, thereby confirming that 'collaborative emission reduction exhibits path dependence'.

Prior studies on supply chain collaborative emission reduction have focused primarily on two-tier or three-tier supply chains. To the best of our knowledge, research on four-tier supply chains is limited. These studies have also shown that factors such as low-carbon product pricing, market promotion intensity, and consumer favour for products with lower carbon emissions directly shape effective market demand, which, in turn, plays a crucial role in influencing the effectiveness of collaborative emission reduction in the supply chain. Against this backdrop, this paper draws on relevant studies and employs a Stackelberg game model to investigate collaborative emission reduction and product pricing strategies in four-tier supply chains. In contrast to other related studies, this study extends the supply chain tiers and incorporates uncertainty in consumer demand for products with lower carbon emissions, with the intent to explore the interaction between supply chain collaborative emission reduction and product pricing strategies.

3 Model assumptions and symbol definitions

3.1 Model assumptions

The model includes one supplier (S), one producer (P), one retailer (R), and consumers. Under carbon tax policies and carbon trading, the producer, as the supply chain leader,

promotes energy conservation and emission reduction. To encourage the supplier to reduce energy use and emissions, the producer offers emission reduction subsidies. Additionally, to increase the retailer's efforts in promoting products with lower carbon emissions, the producer provides specific subsidies. The model assumes that if the supplier's postreduction carbon emissions are below the national quota, the producer will not subsidise the excess. This prevents the supplier from profiting solely from the subsidy. It is also assumed that the carbon reduction level of the final product is a linear function of the supplier's and producer's carbon reduction rates. However, the carbon reduction costs for the supplier and producer are nonlinear functions of their unit product carbon reduction rates.

3.2 Definitions of symbols

e_s : Denotes the carbon emissions generated per unit of raw material production by the supplier prior to the implementation of emission reduction measures.

e_m : Indicates the carbon emissions produced per unit of product processing by the producer before the adoption of emission reduction strategies.

θ_s : Denotes the supplier's carbon reduction rate per unit of raw material production.

θ_m : Denotes the producer's carbon reduction rate per unit of product processing.

p_s : Denotes the supplier's price per unit of raw material sold to the producer.

p_m : Denotes the producer's wholesale price per unit of product.

p_r : Denotes the retailer's retail price per unit of product in the market.

w : Denotes the promotion intensity of the retailer for products with lower carbon emissions, with promotion costs positively correlated with promotion intensity in a nonlinear function. This model assumes $C_r(w) = (1/2)r(w)^2$, and $C_r^{'}(w) > 0$, $C_r^{''}(w) > 0$, with the assumption that $0 \le w < 1$.

t_r : Denotes the proportion of subsidies allocated by the producer to the retailer for promoting products with lower carbon emissions, with the assumption that $0 \le t_r < 1$.

t_s : Denotes the proportion of subsidies from the producer to the supplier for carbon reduction costs, assumed to be within the range of $0 \le t_s < 1$.

D: Denotes the genuine consumer demand that exists in real-world conditions, which is assumed to be $D = Q - \alpha p_r + \beta(\theta_m + \theta_s) + \delta w$; that is, market demand is negatively related to the product's retail price but positively related to the carbon reduction level and the retailer's promotion intensity. Here, *Q* represents the potential market demand for products with lower carbon emissions.

α : market price sensitivity coefficient for products with lower carbon emissions, where $0 < \alpha < 1$.

β: Denotes the carbon reduction sensitivity coefficient, indicating consumer demand increases with higher carbon reduction rates, where $0 < \beta < 1$.

δ: Denotes the sensitivity coefficient for retailer promotion of products with lower carbon emissions, where $0 < \delta < 1$.

c_s: Denotes the supplier's production cost per unit of low-carbon raw material.

c_m: Denotes the producer's unit processing cost for low-carbon product producers.

$C_e(\theta_i e_i)$: Denotes the carbon reduction cost per unit, positively related to the carbon reduction rate and carbon emissions per unit, with $C_e^{'}(\theta_i e_i) > 0$ and $C_e^{''}(\theta_i e_i) > 0$. This model assumes $C_e(\theta_i e_i) = (1/2)e_i(\theta_i)^2$, where $i = s$ or m.

In accordance with the above definitions of symbols, under market demand uncertainty, the total carbon reduction cost for the supplier is $C_e(\theta_s e_s)\mathrm{D}$. Correspondingly, the total carbon reduction cost for the producer's product processing is $C_e(\theta_m e_m)D$. Therefore, the profit functions π_s, π_m, π_r for the supplier, producer, and retailer, respectively, are as follows:

$$\pi_s = [p_s - c_s - (1-t_s)(1/2)e_s(\theta_s)^2]D$$

$$\pi_m = [p_m - p_s - c_m - (1/2)e_m(\theta_m)^2 - (1/2)e_s(\theta_s)^2 t_s]\mathrm{D} - (1/2)r(w)^2 t_r$$

$$\pi_r = (p_r - p_m)D - (1-t_r)(1/2)r(w)^2$$

4 Model analysis

In the collaborative emission reduction strategy, the producer, as the supply chain's leader in carbon reduction, proactively proposes a supply chain-wide plan for collaborative emission reduction and product promotion. This plan includes offering suppliers emission-reduction subsidies and retailers promotion subsidies. Subsequently, the producer sets its product-processing reduction proportion of emissions and the wholesale price of products with lower carbon emissions. Driven by the producer's subsidy and profit-maximisation goals, the supplier selects the reduction proportion of emissions for raw material production. Finally, the retailer, considering consumer sensitivity to low-carbon product prices, emission reduction levels, and promotion intensity, selects the optimal retail price and promotion intensity to maximise its profit. In this study, a Stackelberg game model is adopted to analyse the decision-making process and strategy choices of each supply chain entity under the collaborative emission reduction strategy.

4.1 Retailer's decisions on retail price and promotion intensity

The retailer determines the product's retail price and promotion intensity in response to the wholesale price of the producer's low-carbon product and the promotion subsidy

offered. Meanwhile, consumer demand for products with lower carbon emissions is shaped by the retail price, reduction in the proportion of emissions, and promotion intensity.

Corollary 1:

1 The retailer's profit function shows diminishing marginal returns regarding the retail price and promotion intensity of products with lower carbon emissions. The optimal promotion intensity to maximise the retailer's profit exists if $\delta(p_r - p_m) - (1-t_r)r < 0$, which indicates the retailer cannot directly benefit from the producer's promotion subsidy.

2 To maximise its profit, the retailer's optimal retail price and promotion intensity of products with lower carbon emissions are as follows:

$$p_r^* = \frac{\delta^2 p_m - (1-t_r) r[Q + \beta(\theta_m + \theta_s) + \alpha p_m]}{\delta^2 - 2\alpha r(1-t_r)}$$

$$w^* = -\frac{\delta[Q + \beta(\theta_m + \theta_s) - \alpha p_m]}{\delta^2 - 2\alpha r(1-t_r)}$$

3 The retailer's retail price and promotion intensity are positively related to the producer's promotion subsidy, the producer's product processing carbon reduction rate, and the supplier's raw material production reduction proportion of emissions.

Proof.

1 By calculating the first- and second-order partial derivatives of the retailer's profit function π_r with respect to the retail price p_r and promotion intensity w, we obtain the following:

$$\frac{\partial \pi_r}{\partial p_r} = Q - \alpha p_r + \beta(\theta_m + \theta_s) + \delta w - \alpha(p_r - p_m) \tag{1}$$

$$\frac{\partial^2 \pi_r}{\partial p_r^{\,2}} = -2\alpha < 0 \tag{2}$$

$$\frac{\partial \pi_r}{\partial w} = \delta(p_r - p_m) - (1-t_r) r w \tag{3}$$

$$\frac{\partial^2 \pi_r}{\partial w^2} = -(1-t_r) r < 0 \tag{4}$$

Since $D - \alpha(p_r - p_m) > 0$, it follows that $\frac{\partial \pi_r}{\partial p_r} > 0$, indicating that the retailer's profit function π_r is convex in the retail price p_r. Additionally, as $\frac{\partial^2 \pi_r}{\partial p_r^{\,2}} = -2\alpha < 0$, the retailer's profit function exhibits diminishing marginal returns with respect to the retail

price p_r. Similarly, on the basis of equations (3) and (4), the retailer's profit function π_r is also convex in the promotion intensity w and exhibits diminishing marginal returns.

Further analysis reveals that $\lim_{p_r \to 0} \frac{\partial \pi_r}{\partial p_r} = Q + \alpha p_m + \beta(\theta_m + \theta_s) + \delta w > 0$ and that $\lim_{p_r \to \infty} \frac{\partial \pi_r}{\partial p_r} = -\infty < 0$. Thus, for the retail price $p_r \in (0, +\infty)$, there exists an optimal retail price p_r^* that maximises the retailer's profit, i.e., $\frac{\partial \pi_r}{\partial p_r^*}(p_r^*, w) = 0$. Similarly, since $\lim_{w \to 0} \frac{\partial \pi_r}{\partial w} = \delta(p_r - p_m) > 0$ and $\lim_{w \to 1} \frac{\partial \pi_r}{\partial w} = \delta(p_r - p_m) - (1 - t_r)r$, if and only if $\delta(p_r - p_m) - (1 - t_r)r < 0$, then $\lim_{w \to 1} \frac{\partial \pi_r}{\partial w} < 0$. This implies that for the promotion intensity $w \in [0,1)$, there exists an optimal promotion intensity w^* that maximises the retailer's profit, i.e., $\frac{\partial \pi_r}{\partial w^*}(p_r, w^*) = 0$.

2 By performing first-order optimisation on the retailer's profit function π_r with respect to the retail price p_r and promotion intensity w and setting the partial derivatives equal to zero, we obtain the following equations:

$$Q - \alpha p_r^* + \beta(\theta_m + \theta_s) + \delta w^* - \alpha(p_r^* - p_m) = 0 \tag{5}$$

$$\delta(p_r^* - p_m) - (1 - t_r) r w^* = 0 \tag{6}$$

By simultaneously solving equations (5) and (6), the optimal retail price p_r^* and the optimal product promotion intensity w^* for the retailer is obtained.

$$p_r^* = \frac{\delta^2 p_m - (1 - t_r) r[Q + \beta(\theta_m + \theta_s) + \alpha p_m]}{\delta^2 - 2\alpha r(1 - t_r)}$$

$$w^* = -\frac{\delta[Q + \beta(\theta_m + \theta_s) - \alpha p_m]}{\delta^2 - 2\alpha r(1 - t_r)}$$

3 To examine the sensitivity of the retailer's optimal retail price p_r^* and optimal promotion intensity w^* with respect to the product promotion subsidy t_r, the producer's reduction proportion of emissions θ_m, and the supplier's reduction proportion of emissions θ_s, we calculate the partial derivatives $\frac{\partial p_r^*}{\partial t_r}$, $\frac{\partial p_r^*}{\partial \theta_m}$, $\frac{\partial p_r^*}{\partial \theta_s}$, $\frac{\partial w^*}{\partial t_r}$, $\frac{\partial w^*}{\partial \theta_m}$ and $\frac{\partial p_r^*}{\partial \theta_s}$. The specific results are as follows:

$$\frac{\partial p_r^*}{\partial t_r} = \delta^2 r \frac{[Q + \beta(\theta_m + \theta_s) - \alpha p_m]}{\left(\delta^2 - 2\alpha r(1 - t_r)\right)^2} > 0,\ \frac{\partial p_r^*}{\partial \theta_m} = \frac{\partial p_r^*}{\partial \theta_s} = \frac{-\beta r(1 - t_r)}{\delta^2 - 2\alpha r(1 - t_r)} > 0,$$

$$\frac{\partial w^*}{\partial t_r} = \frac{2\delta[Q + \beta(\theta_m + \theta_s) - \alpha p_m]}{\alpha r(\delta^2 - 2\alpha r + 2\alpha r t_r)^2} > 0, \text{ and } \frac{\partial w^*}{\partial \theta_m} = \frac{\partial p_r^*}{\partial \theta_s} = \frac{-\beta\delta}{\delta^2 - 2\alpha r(1 - t_r)} > 0.$$

Given that $Q+\beta(\theta_m+\theta_s)-\alpha p_r>0$ and $p_r>p_m$, it follows that $Q+\beta(\theta_m+\theta_s)-\alpha p_m>0$. According to the model assumptions and the above derivations, $p_r^*>0$ and $w^*\geq 0$, it is concluded that $\delta^2-2\alpha r(1-t_r)<0$. Further analysis reveals that $\delta^2 p_m-(1-t_r)r[Q+\beta(\theta_m+\theta_s)+\alpha p_m]<0$. Therefore, $\frac{\partial p_r^*}{\partial t_r}>0$, $\frac{\partial p_r^*}{\partial \theta_m}=\frac{\partial p_r^*}{\partial \theta_s}>0$, $\frac{\partial w^*}{\partial t_r}>0$ and $\frac{\partial w^*}{\partial \theta_m}=\frac{\partial p_r^*}{\partial \theta_s}>0$.

In summary, the retailer's optimal retail price and promotion intensity are positively related to the producer's promotion subsidy and the carbon reduction rates of both the producer and the supplier. This suggests that enhancing the producer's promotion subsidy and both parties' carbon reduction rates can increase the retailer's promotion intensity and lead to higher retail prices.

4.2 Producer's carbon reduction decisions

The producer selects the optimal product processing carbon reduction rate to maximise its profit, considering the retailer's retail price and promotion strategy.

Corollary 2:

1 The producer's profit function is convex in its product processing carbon reduction rate, ensuring an optimal rate for profit maximisation.

2 The optimal reduction proportion of emissions for the producer, maximising its profit, is as follows:

$$\theta_m^*=\frac{2\sqrt{e_m^2(Q-\alpha p_r+\beta\theta_s+\delta w)^2+3e_m\beta^2[2(p_m-p_s-c_m)-e_s\theta_s^2 t_s]}-2e_m(Q-\alpha p_r+\beta\theta_s+\delta w)}{6\beta e_m}$$

3 The producer's product-processing carbon reduction rate is negatively correlated with the supplier's raw material production carbon reduction rate, retail price, and carbon reduction and promotion subsidies.

Proof.

1 By calculating the first- and second-order partial derivatives of the producer's profit function π_m with respect to its product-processing reduction proportion of emissions θ_m, we obtain the following results:

$$\frac{\partial \pi_m}{\partial \theta_m}=\beta[p_m-p_s-c_m-\frac{1}{2}e_m(\theta_m)^2-\frac{1}{2}e_s(\theta_s)^2 t_s]-e_m\theta_m[Q-\alpha p_r+\beta(\theta_m+\theta_s)+\delta w]$$

$$\frac{\partial^2 \pi_m}{\partial {\theta_m}^2}=-e_m\left[Q-\alpha p_r+\beta(\theta_m+\theta_s)+\delta w\right]-2\beta e_m\theta_m$$

According to the model assumptions, the revenue from carbon reduction exceeds its associated costs, leading to $\frac{\partial \pi_m}{\partial \theta_m}>0$ and $\frac{\partial^2 \pi_m}{\partial {\theta_m}^2}<0$. This finding indicates that the

producer's profit function is convex in its product processing carbon reduction rate, with diminishing marginal returns as the reduction rate increases. Additionally, since $\lim_{\theta_m \to 0} \frac{\partial \pi_m}{\partial \theta_m} = \beta[p_m - p_s - c_m - \frac{1}{2} e_s \theta_s^2 t_s] > 0$ and $\lim_{\theta_m \to 1} \frac{\partial \pi_m}{\partial \theta_m} = -\infty < 0$, there exists an optimal reduction in the proportion of emissions $\theta_m^* \in [0,1)$ that maximises the producer's profit, i.e., $\frac{\partial \pi_m}{\partial \theta_m^*}(\theta_m^*) = 0$.

2 By performing first-order optimisation on the producer's profit function π_m with respect to its product processing carbon reduction rate θ_m, we set the derivative equal to zero:

$$\frac{\partial \pi_m}{\partial \theta_m^*} = \beta\left[p_m - p_s - c_m - \frac{1}{2} e_m (\theta_m^*)^2 - \frac{1}{2} e_s \theta_s^2 t_s\right], \\ - e_m \theta_m^* \left[Q - \alpha p_r + \beta(\theta_m^* + \theta_s) + \delta w\right] = 0$$

from which we can derive the optimal carbon reduction rate θ_m^*.

$$\theta_m^* = \frac{\sqrt{e_m^2 (Q - \alpha p_r + \beta\theta_s + \delta w)^2 + 3 e_m \beta^2 [2(p_m - p_s - c_m) - e_s \theta_s^2 t_s]} - e_m (Q - \alpha p_r + \beta\theta_s + \delta w)}{3\beta e_m}$$

3 By taking the first-order derivatives of the producer's optimal product processing carbon reduction rate θ_m^* with respect to the supplier's carbon reduction subsidy t_s, product promotion intensity w, the supplier's carbon reduction rate θ_s, and the retail price p_r, we obtain the following results:

$$\frac{\partial \theta_m^*}{\partial t_s} = \frac{-\beta e_s \theta_s^2}{2\sqrt{4 e_m^2 (Q - \alpha p_r + \beta\theta_s + \delta w)^2 + 6 e_m \beta^2 [2(p_m - p_s - c_m) - e_s \theta_s^2 t_s]}} < 0$$

$$\frac{\partial \theta_m^*}{\partial w} = \frac{e_m^2 \delta}{3}\left[\frac{(Q - \alpha p_r + \beta\theta_s + \delta w)}{\sqrt{e_m^2 (Q - \alpha p_r + \beta\theta_s + \delta w)^2 + 3 e_m \beta^2 [2(p_m - p_s - c_m) - e_s \theta_s^2 t_s]}} - \beta\right] < 0$$

$$\frac{\partial \theta_m^*}{\partial \theta_s} = \frac{e_m \beta}{3}\left[\frac{(Q - \alpha p_r + \beta\theta_s + \delta w) - 3\beta e_s \theta_s t_s}{\sqrt{e_m^2 (Q - \alpha p_r + \beta\theta_s + \delta w)^2 + 3 e_m \beta^2 [2(p_m - p_s - c_m) - e_s \theta_s^2 t_s]}} - 1\right] < 0$$

$$\frac{\partial \theta_m^*}{\partial p_r} < 0$$

Thus, the producer's optimal product-processing reduction proportion of emissions decreases with an increase in the supplier's raw material production reduction proportion of emissions, an increase in the producer's carbon emission reduction subsidy to the supplier, or an increase in the retailer's product promotion intensity.

4.3 Supplier's carbon reduction decisions for raw material production

Considering the producer's product processing carbon reduction, retail pricing, and promotion strategies and accounting for consumers' sensitivity to the retail price and carbon reduction rate of products with lower carbon emissions, the supplier selects the optimal raw material production carbon reduction rate to maximise its profit.

Corollary 3:

1 When the producer provides a carbon reduction subsidy, the supplier has an optimal raw material production carbon reduction rate that maximises its profit.

2 Under the producer's carbon reduction subsidy, the supplier's optimal reduction proportion of emissions is as follows:

$$\theta_s^* = (1/2)\frac{2e_s(1-t_s)(Q-\alpha p_r+\beta\theta_m+\delta w)+2\sqrt{T}}{3\beta e_s(1-t_s)}$$

3 The supplier's reduction in the raw material production proportion of emissions is positively correlated with the producer's carbon emission reduction subsidy but negatively correlated with the producer's product processing reduction proportion of emissions and the promotion subsidy granted to the retailer.

Proof.

1 By taking the first-order and second-order partial derivatives of the supplier's profit function π_s with respect to the raw material production carbon reduction rate θ_s, we obtain the following:

$$\frac{\partial \pi_s}{\partial \theta_s} = \beta[p_s - c_s - (1/2)(1-t_s)e_s\theta_s^2] - (1-t_s)\theta_s e_s\left[Q-\alpha p_r+\beta(\theta_s+\theta_m)+\delta w\right]$$

$$\frac{\partial^2 \pi_s}{\partial {\theta_s}^2} = (t_s-1)e_s\left[Q-\alpha p_r+\beta(\theta_s+\theta_m)+\delta w\right]+2(t_s-1)\beta e_s\theta_s$$

Since $(t_s-1)<0$, it follows that $\frac{\partial^2 \pi_s}{\partial {\theta_s}^2}<0$. Additionally, $\lim_{\theta_s\to 0}\frac{\partial \pi_s}{\partial \theta_s}>0$ and $\lim_{\theta_s\to 1}\frac{\partial \pi_s}{\partial \theta_s}=-\infty<0$. Thus, the supplier's profit function is convex in its raw material production carbon reduction rate, and there exists an optimal carbon reduction rate $\theta_s^* \in [0,1)$ that maximises the supplier's profit, i.e., $\frac{\partial \pi_s}{\partial \theta_s^*}(\theta_s^*)=0$.

2 By performing first-order optimisation on the supplier's profit function π_s with respect to the optimal raw material production carbon reduction rate θ_s^* and setting $\frac{\partial \pi_s}{\partial \theta_s^*}=0$, we obtain the following:

$$\theta_s^* = (1/2)\frac{2e_s(1-t_s)(Q-\alpha p_r+\beta\theta_m+\delta w)-2\sqrt{T}}{3\beta e_s(1-t_s)}$$

where $T = e_s^2(1-t_s)^2\{(Q-\alpha p_r+\beta\theta_m+\delta w)^2-2\left[\alpha p_r(Q+\beta\theta_m)+\beta\theta_m\delta w(1+t_s)\right]\}$ $+6(1-t_s)(p_s-c_s)e_s\beta^2$.

3 Taking the first-order derivatives of the optimal raw material carbon reduction rate θ_s^* with respect to the producer's subsidy t_s, retail price p_r, product processing carbon reduction rate θ_m, and promotion intensity w, we find that $\frac{\partial\theta_s^*}{\partial t_s}>0$, $\frac{\partial\theta_s^*}{\partial p_r}>0$, $\frac{\partial\theta_s^*}{\partial\theta_m}<0$ and $\frac{\partial\theta_s^*}{\partial w}<0$. Thus, the producer's carbon reduction subsidy to the supplier encourages a higher raw material carbon reduction rate, whereas the producer's subsidy for the retailer's low-carbon product promotion leads to a lower rate. Additionally, an increase in the producer's product processing carbon reduction rate reduces the incentive for the supplier to increase the raw material production carbon reduction rate.

4.4 Producer's optimal wholesale price decisions

On the basis of the retailer's optimal retail price and promotion intensity decisions for products with lower carbon emissions and in conjunction with the supplier's raw material production carbon reduction rate, the producer further optimises the wholesale price of products with lower carbon emissions and the product processing carbon reduction rate to maximise its own profit.

Corollary 4:

1 In response to the retailer's optimal retail price, product promotion intensity, and the supplier's raw material carbon reduction rate, there exists an optimal wholesale price for the producer that maximises its profit.

2 With respect to the retailer's optimal retail price and the promotion intensity of products with lower carbon emissions, the producer's optimal wholesale price is as follows:

$$p_m^* = \frac{2M\left[2\alpha r\left(1-t_r^*\right)^2-\delta^2\left(1-2t_r^*\right)\right]+\alpha\left(1-t_r^*\right)K[2\left(e_m\theta_m^2p_s+c_m\right)-B]}{2\alpha[\left(3t_r^*-2\right)\delta^2+2r\alpha(1-t_r^*)^2]}$$

3 The producer's optimal wholesale price is positively associated with the carbon emission reduction in its product processing and the supplier's raw material carbon emission reduction, as well as the subsidies for the supplier's carbon emission reduction and the retailer's low-carbon product promotion.

Proof.

1 By substituting the retailer's optimal retail price p_r^* and the promotion intensity w^* of products with lower carbon emissions into the producer's profit function and taking the first-order and second-order derivatives with respect to the product's wholesale price, we obtain the following:

$$\frac{\partial \pi_m}{\partial p_m} = \frac{\alpha^2 r\left(1-t_r^*\right)[p_m + \delta^2 p_m - p_s - c_m - e_m \theta_m^{*2} - \left(\frac{1}{2}\right) e_s \theta_s^{*2} t_s^*] + \delta^2 \alpha p_m}{\delta^2 - 2r\alpha(1-t_r^*)}$$

$$+ \frac{\alpha r[\delta^2 - \alpha r\left(1-t_r^*\right)^2](Q - \alpha p_m + \beta\left(\theta_m^* + \theta_s^*\right))}{[\delta^2 - 2r\alpha(1-t_r^*)]^2}$$

$$\frac{\partial^2 \pi_m}{\partial p_m^{\ 2}} = \alpha^2 r \frac{2\left(1-t_r^*\right)\left(\delta^2 - 2\alpha r\left(1-t_r^*\right)\right) - \delta^2 t_r^*}{\left(\delta^2 - 2\alpha r\left(1-t_r^*\right)\right)^2} = \alpha^2 r \frac{\delta^2\left(2-3t_r^*\right) + 4\alpha r\left(1-t_r^*\right)^2}{\left(\delta^2 - 2\alpha r\left(1-t_r^*\right)\right)^2}$$

Because $\lim_{p_m \to 0} \frac{\partial \pi_m}{\partial p_m} > 0$ and $\lim_{p_m \to +\infty} \frac{\partial \pi_m}{\partial p_m} < 0$, combined with $1 - t_r^* > 0$ and $\delta^2 - 2\alpha r\left(1-t_r^*\right) < 0$, it follows that $\frac{\partial^2 \pi_m}{\partial p_m^{\ 2}} < 0$. Thus, given the optimal retail price, promotion intensity, and the supplier's optimal carbon reduction rate, there exists an optimal wholesale price for the producer to maximise profit.

2 By performing first-order optimisation on the producer's profit function π_m with respect to the optimal wholesale price p_m^*, setting $\frac{\partial \pi_m}{\partial p_m^*} = 0$, we obtain the following:

$$p_m^* = \frac{2M\left[2\alpha r\left(1-t_r^*\right)^2 - \delta^2\left(1-2t_r^*\right)\right] + \alpha\left(1-t_r^*\right)K[2\left(e_m \theta_m^{*2} p_s + c_m\right) - B]}{2\alpha[\left(3t_r^* - 2\right)\delta^2 + 2r\alpha(1-t_r^*)^2]}$$

3 By calculating the first-order derivatives of the optimal wholesale price, p_m^*, with respect to the supplier's carbon reduction rate θ_s^*, the producer's product processing carbon reduction rate θ_m^*, the producer's carbon reduction subsidy to the supplier t_s^*, and the producer's promotion subsidy for products with lower carbon emissions to the retailer t_r^*, we find the following results:

$$\frac{\partial p_m^*}{\partial \theta_s^*} = \frac{2\alpha\beta\left(1-t_r^*\right)^2 - \beta\delta^2 - \alpha e_s \theta_s^* t_s^*\left(1-t_r^*\right)K}{\alpha N} > 0,$$

$$\frac{\partial p_m^*}{\partial \theta_m^*} = -\frac{4\alpha\beta r\left(1-t_r^*\right)^2 + 2\beta\delta^2\left(1-2t_r^*\right) + 8\alpha e_m \theta_m^*\left(1-t_r^*\right)K}{\alpha N} > 0,$$

$$\frac{\partial p_m^*}{\partial t_s^*} = \frac{-\alpha e_s \theta_s^{*2}\left(1-t_r^*\right)K}{\alpha N} > 0 \text{ and}$$

$$\frac{\partial p_m^*}{\partial t_r^*} = \frac{-8\alpha r\left(1-t_r^*\right)[A+M-Q]+4QK+4\beta\theta_m^*\delta^2+\alpha B\delta^2}{2\alpha N}$$

$$-\frac{\alpha r\left(1-t_r^*\right)^2[4A+4M+2\alpha B]+2\delta^2\left(1-2t_r^*\right)M-\delta^2\left(1-t_r^*\right)[2A+\alpha B]}{2\alpha N^2} > 0$$

where $\alpha\left(p_s+c_m+e_m\theta_m^{*2}\right)=A$, $e_s\theta_s^{*2}t_s^*=B$, $Q+\beta\left(\theta_s^*+\theta_m^*\right)=M$, $4\alpha r\left(1-t_r^*\right)^2+\delta^2\left(3t_r^*-2\right)=N$, and $\delta^2-2\alpha r\left(1-t_r^*\right)=K$.

The producer is encouraged to raise the wholesale price by the supplier's and its own carbon reduction rates. Subsidies for the supplier's carbon reduction and the retailer's product promotion also further encourage this price increase.

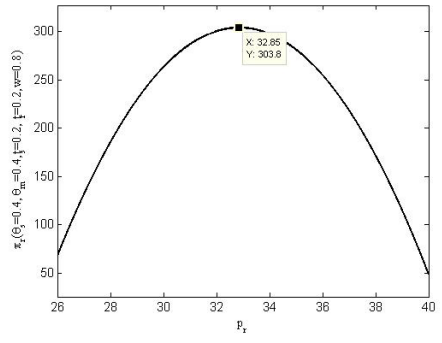
5 Numerical example verification

Consider an energy-saving and emission-reduction supply chain that is comprised of a supplier, a producer, a retailer, and the consumers. Both the supplier's unit raw material production cost and the producer's unit product processing cost are set to 1. Similarly, in the prereduction state, both the supplier's unit raw material carbon emissions and the producer's unit product processing carbon emissions are set to 2; i.e., $c_s=c_m=1$ and $e_s=e_m=2$. The retailer's promotion cost for products with lower carbon emissions is $r=20$. The market potential demand for products with lower carbon emissions is $Q=200$, and the consumer sensitivity coefficients to the price, carbon reduction rate, and promotion intensity of products with lower carbon emissions are $\alpha=5$, $\beta=4$ and $\delta=0.5$, respectively.

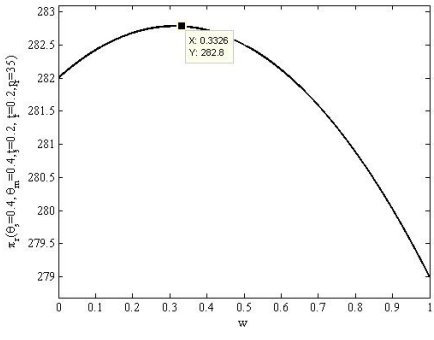
5.1 Sensitivity analysis of retailer's profit and product retail price

First, as indicated in Figure (1-1) and (1-2), the retailer's profit does not continuously increase with the retail price and promotion intensity when consumers are sensitive to these factors. Rather, an optimal combination of retail price and promotion intensity exists that maximises the retailer's profit. Second, the producer's promotion subsidy for products with lower carbon emissions and the carbon reduction rate in product processing both drive the retailer to increase promotion efforts (see Figure 1-4). The subsidy directly cuts promotion costs, while the carbon reduction rate indirectly increases retailer profits through consumer sensitivity. Given the indirect and uncertain nature of the latter, the producer's promotion subsidy has a more direct and significant effect on increasing the retailer's promotion intensity.

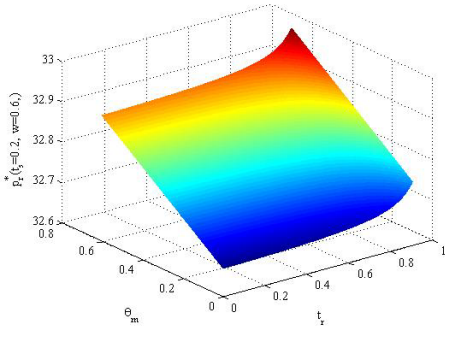
Figure 1 Sensitivity responses of retailer's profit, product retail price, and promotion intensity (see online version for colours)



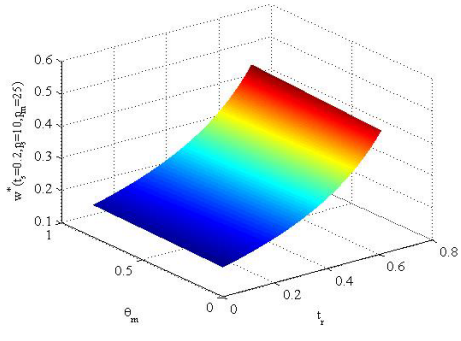
(1-1) *Sensitivity Response of* π_r *to* p_r



(1-2) Sensitivity Response of π_r tow



(1-3) Sensitivity Response of p_r^* to θ_m and t_r



(1-4)Sensitivity Response of w^* to θ_m andt_r

Finally, similar to the changes in the retailer's promotion intensity, increasing the promotion subsidy and the product processing carbon reduction rate prompts the retailer to raise the retail price (see Figure 1-3). Intensifying product promotion and enhancing carbon reduction increases product visibility, thus attracting more consumers. Given the high sensitivity of consumers to the product's carbon reduction rate, retailers increase the retail price to increase their profits.

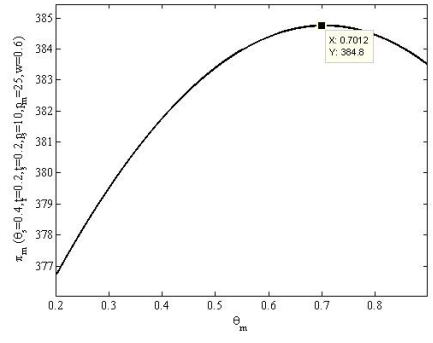
5.2 Sensitivity analysis of producer's profit and carbon reduction rate

The producer's profit does not rise monotonically with the product-processing carbon reduction rate. Instead, there is an optimal rate that maximises profit (see Figure 2-1). Moreover, to maximise the producer's profit, there are optimal levels of promotion subsidies to the retailer and carbon reduction subsidies to the supplier, with the retailer's subsidy having a more significant impact (see Figure 2-2).

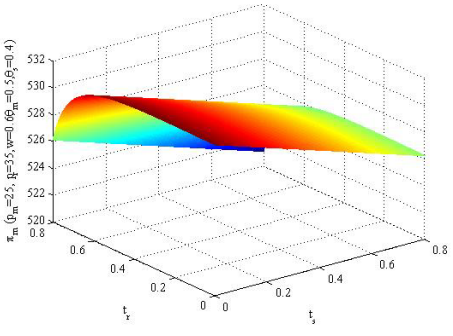
Raising the producer's product-processing carbon reduction rate or the supplier's raw material carbon reduction rate can increase the wholesale price, with the former exhibiting a more significant impact (see Figure 2-3). Moreover, increasing the supplier's carbon reduction subsidy and the retailer's promotion subsidy also leads to a higher wholesale price, where the retailer's promotion subsidy has a greater effect (see Figure 2–4). This occurs because promotion subsidies not only encourage retailers to

promote products more actively but also to increase product visibility, thereby influencing market demand.

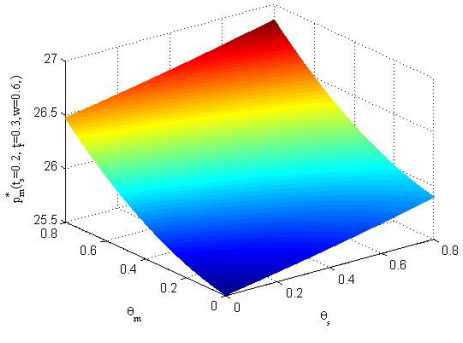
Figure 2 Sensitivity responses of the producer's profit, carbon reduction rates, and optimal wholesale price (see online version for colours)



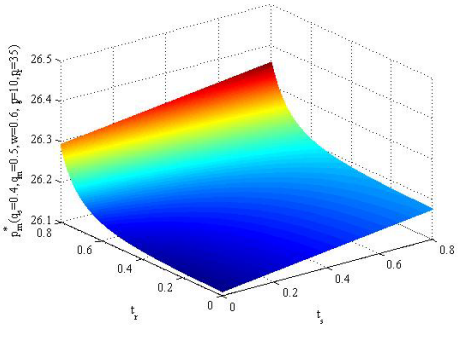
(2-1) Sensitivity Response of π_m to θ_m



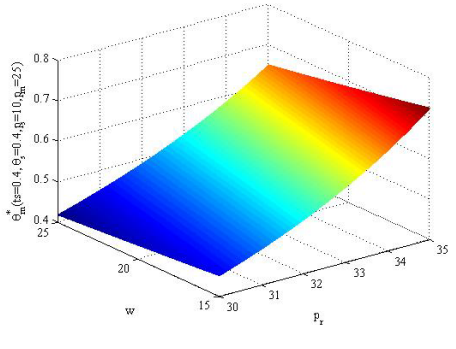
(2-2) Sensitivity Response of π_m to t_r andt_s



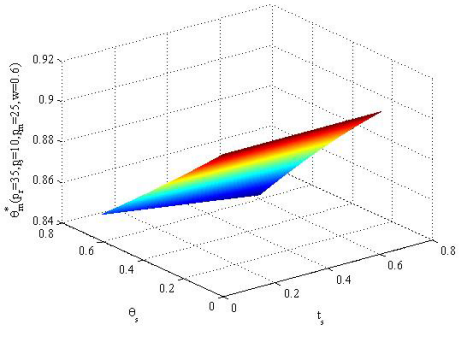
(2-3) Sensitivity Response of p_m^* to θ_m and θ_s



(2-4) Sensitivity Response of p_m^* to t_r andt_s



(2-5) Sensitivity Response of θ_m^* to w and p_r



(2-6) Sensitivity Response of θ_m^* to $\theta_s$andt_s

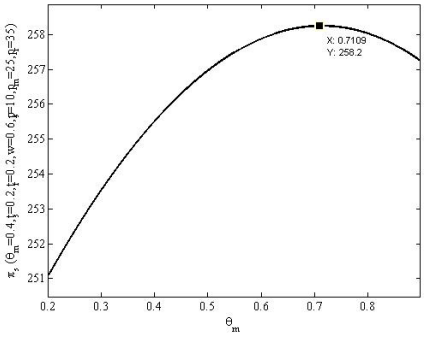
Finally, although an increase in the retailer's product promotion intensity may encourage the producer to increase the product processing carbon reduction rate, this increase in promotion intensity can conversely diminish the producer's motivation to increase the

carbon reduction rate (see Figure 2-5). Similarly, while subsidies for the supplier's raw material carbon reduction can prompt the supplier to increase its carbon reduction rate, this increase can paradoxically lead to a decrease in the producer's product processing carbon reduction rate (see Figure 2-6).

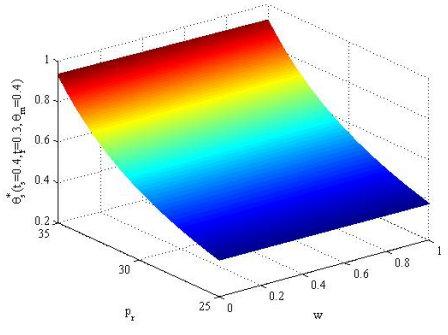
5.3 Sensitivity analysis of suppliers' profit and carbon reduction rate

First, akin to the producer's optimal product processing carbon reduction rate and the retailer's optimal product promotion intensity, there is an optimal raw material carbon reduction rate for the supplier in the joint carbon reduction and product pricing strategy, which maximises the supplier's profit (see Figure 3-1).

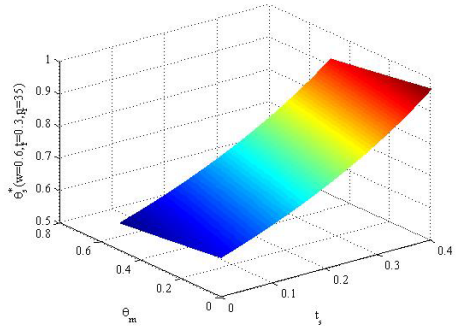
Figure 3 Sensitivity responses of supplier's profit and carbon reduction rate (see online version for colours)



(3-1) Sensitivity Response of π_s toθ_s



(3-2) Sensitivity Response of θ_s^* to w and p_r



(3-3) Sensitivity Response of θ_s^* to t_s and q_m

Second, the supplier's raw material carbon reduction rate is influenced by the producer's carbon reduction subsidy and indirectly by the producer's product processing carbon reduction rate, the retailer's promotion intensity, and the retail price. The producer's raw material carbon reduction subsidy strengthens the supplier's emission reduction motivation. However, the increase in the carbon reduction rate of the producer's product processing results in a decrease in the supplier's raw material carbon reduction rate (see Figure 3-3).

Finally, an increase in the retail price enhances the supplier's motivation to reduce raw material carbon emissions, whereas intensified product promotion has the opposite effect. If the revenue from the demand growth driven by the retailer's promotion is insufficient to cover the carbon reduction costs, the supplier, aiming to maximise its profit, reduces its raw material carbon reduction rate. This shifts the emission reduction burden to the producer's product processing stage, thereby lowering raw material costs.

6 Conclusions and recommendations

In this study, the collaborative emission reduction and pricing strategies of a four-stage supply chain were analysed and simulated, and the following conclusions were drawn:

1 Under market demand uncertainty, each supply chain node has an optimal decision-making combination to maximise revenue. Hence, Pareto improvement can be achieved by optimising variables such as raw material wholesale prices, carbon reduction rates, product wholesale prices, and retail prices.

2 The supplier's raw material carbon reduction rate is influenced by the producer's carbon reduction rate and subsidies and is indirectly affected by the retailer's price and promotion intensity. Furthermore, the supplier's carbon reduction rate is negatively related to the producer's product processing carbon reduction rate, the retailer's promotion intensity, and the retail prices.

3 Subsidies for raw material carbon reduction and product promotion increase the producer's costs, leading to higher wholesale prices, with the latter subsidy having a greater effect. Additionally, owing to consumer preference for products with lower carbon emissions, greater carbon reduction in raw material production and product processing can lead to higher wholesale prices.

4 The higher the promotion subsidy is, the greater the impact of the retailer's promotion intensity on its revenue. Given that retail prices are positively related to the carbon reduction rates of raw materials and product processing, higher promotion subsidies and stronger consumer preference for products with lower carbon emissions result in higher retail prices.

5 Emission reduction subsidies follow the law of diminishing marginal utility. When the producer's subsidy for the supplier's emission reduction reaches a threshold, it triggers a resource crowding-out effect, which then lowers the producer's own emission reduction rate. Moreover, moderately reducing the retailer's promotion subsidy can encourage lower retail prices and enhance overall supply chain emission reduction efficiency.

From the perspective of supply chain collaborative emission reduction, increasing the producer's subsidy for the supplier's raw material carbon emission reduction can enhance the raw material reduction proportion of emissions, but it reduces the producer's own product processing reduction proportion of emissions. Notably, decreasing the retailer's promotion subsidy also reduces the producer's carbon emission reduction costs and lessens the retailer's promotion intensity. This allows the producer to increase the product

processing reduction proportion of emissions and helps the retailer reduce product retail prices, thereby offsetting market fluctuations from decreased promotion intensity.

Research findings indicate that retailers, as pivotal nodes on the demand side, create an emission reduction mechanism through price signalling and marketing promotion, thus holding a strategic position comparable to that of the production stage. The Stackelberg game model developed in this study provides a decision-making framework for collaborative emission reduction in a four-level supply chain, revealing the collaborative path of subsidy policies and market mechanisms. Future research could explore multistage dynamic game scenarios with a focus on contract design under information asymmetry and the collaborative mechanism of multiagent carbon accounts supported by blockchain technology.

Competing interests

The authors declare that no competing interests exist.

Data availability statement

Data sharing is not applicable to this paper, as no datasets were generated or analysed during the current study.

Ethical statement

Not applicable.

Consent to publish

The author of this paper has agreed to the publication of this paper.

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