frontiers | Frontiers in Physics

TYPE Original Research
PUBLISHED 29 January 2026
DOI 10.3389/fphy.2025.1686006

OPEN ACCESS

EDITED BY
Benjamin Miranda Tabak,
Fundação Getúlio Vargas, Brazil

REVIEWED BY
Fuqiang Wang,
Central South University, China
Ran Wu,
Southeast University, China

*CORRESPONDENCE
Shanshan Xie,
xiess@hnu.edu.cn
Jiamuyan Xie,
jiamuyanxie@hnu.edu.cn

RECEIVED 06 September 2025
REVISED 18 November 2025
ACCEPTED 22 December 2025
PUBLISHED 29 January 2026
CORRECTED 02 February 2026

CITATION
Xie S and Xie J (2026) The signal strategy in low-carbon supply chains.
Front. Phys. 13:1686006.
doi: 10.3389/fphy.2025.1686006

The signal strategy in low-carbon supply chains

Shanshan Xie[1,2]* and Jiamuyan Xie[3]*

[1]School of Economics and Management, Hunan University of Technology, Zhuzhou, Hunan, China, [2]College of Economics and Trade, Hunan University, Changsha, Hunan, China, [3]Business School, Hunan First Normal University, Changsha, Hunan, China

Introduction: This research examines a low-carbon supply chain involving a vertically integrated manufacturer with private market demand information and a retailer that sources low-carbon products. The two parties engage in quantity competition.
Methods: We establish a dynamic signaling game model to analyze how the manufacturer can use its output and carbon emission reduction level signaling demand information to the retailer under asymmetric conditions.
Results: Our findings indicate that (1) the manufacturer must always distort its quantities and carbon emission reduction levels downward to signal low demand; (2) the inference effect worsens the situation of the manufacturer and the retailer; (3) manufacturer's signaling strategies are influenced by several factors, such as market demand volatility, the prior probability of market demand, its capacity for reducing emission, and consumers preferences for low-carbon products.
Discussion: The novelty of this research lies in incorporating demand information asymmetry into the manufacturer's output and carbon emission reduction strategies, providing valuable insights for low-carbon supply chains to coordinate the most appropriate signaling strategies.

KEYWORDS

low-carbon supply chain, supply chain management, carbon emission reduction level, signaling game model, asymmetric information

1 Introduction

Climate change is a critical issue confronting the global community [1]. As highlighted by the United Nations Intergovernmental Panel on Climate Change (IPCC), the sustained rise in global temperatures has led to a series of severe issues, including increased frequency of natural disasters, the rise in sea levels, and significant ecosystem degradation [2]. In response to this critical challenge, governments worldwide have introduced stringent carbon emission regulations and policies to encourage businesses to lower their carbon footprint [3].The European Union has committed to achieving carbon neutrality by 2050, for example,. China has established a "double carbon" strategy, targeting to peak carbon emissions before 2030 and achieve carbon neutrality before 2060 [4]. The introduction of these policies has made low-carbon transition a vital direction for economic development [5]. Simultaneously, as public environmental awareness has significantly increased, consumer attention to low-carbon products has grown substantially [6]. More and more consumers are beginning to emphasize the carbon footprint of products and prefer to choose environmentally friendly vehicles, energy-efficient appliances, and sustainable fashion items [7]. A recent study reveals that

77.60% of respondents place greater emphasis on sustainability certifications and low-carbon labels when purchasing goods [8]. This shift in consumer preferences, driven by both low-carbon policies and green consumer preferences, has further stimulated market demand for the supply chain [9]. To meet the growing consumer demand, businesses are compelled to implement strategies to cut carbon emissions throughout the supply chain, thereby building a more sustainable system [10]. Multinational corporations such as Hitachi, Tesa, Nestlé, and P&G have already announced their commitments to achieving net-zero emissions across their entire supply chains by 2050 or earlier.

However, in low-carbon supply chains, member enterprises face the critical challenge of demand information asymmetry, particularly during the initial stages of introducing low-carbon products to the market. Manufacturers often possess a more comprehensive understanding of market demand [11]. During the initial phases of product development, manufacturers allocate substantial resources to conducting market analysis to ensure a close alignment between product design and market needs [12,13]. However, in certain situations, retailers may struggle to accurately grasp the diversity of consumer demands, leading to a disconnect between the products they sell and market requirements. In the new energy vehicle sector, for example, some retailers cannot keep pace with growing consumer demand and are slow to adjust their vehicle configurations [14]. Asymmetric demand information weakens a supply chain's market competitiveness by inducing operational inefficiencies such as product shortages and inventory backlogs [15]. In fact, information within supply chains is both a vital asset and a key driver of decision-making. [16]. For example, Xiaomi, a mobile phone manufacturing company, exemplifies this approach by sharing real-time market demand data. This allows for dynamic adjustments to their production plans and helps avoid potential surplus due to market fluctuations. Thus, conducting in-depth research on demand information asymmetry between manufacturers and retailers holds significant theoretical and practical value.

Based on earlier discussions, we aim to investigate the signaling strategies used by the manufacturer to disclose demand information to the competing retailer. Existing literature has established that output serves as an effective demand signal in traditional supply chains [17], while carbon emission reduction levels have also been demonstrated to possess signaling functionality in low-carbon contexts [11]. Previous research has predominantly focused on single signal frameworks, whereas the manufacturer's decisions in reality are multi-dimensional. Therefore, this study develops a signal game model to examine how the manufacturer strategically combines output and carbon emission reduction levels as complementary signals to convey market demand. It is noteworthy that different types of manufacturers may adopt differentiated signaling strategies depending on market conditions. For instance, when demand fluctuates significantly, a high-demand manufacturer sets a higher emission reduction level to signal her type, prompting the retailer to place correspondingly larger orders [11]. Conversely, under mild market fluctuations, a low-demand manufacturer may mimic the output decisions of a high-type to secure larger orders and capture excess returns [18]. Motivated by these considerations, this study focuses on examining the strategic interactions between different manufacturer types within separating and pooling equilibria, addressing the following research questions:

1. What is the manufacturer's decision for signaling market demand to achieve a separating equilibrium?
2. What is the manufacturer's decision for signaling market demand to achieve a pooling equilibrium?
3. What are the key factors influencing the manufacturer's signaling strategies?

To investigate the research questions discussed, we develop a signaling model between a low-carbon product manufacturer and a retailer operating in a competitive product market. In this framework, the manufacturer first determines her production output and carbon emission reduction levels. Following this, the retailer, after observing the manufacturer's decisions, determines the order quantity. Together, they supply products to the end market.

This study contributes significantly to supply chain management, specifically in the following areas: (1) Unlike studies on carbon reduction under information symmetry, this study identifies the operational strategies for effective signaling under demand asymmetry. Model analysis indicates that to accurately signal low market demand, the manufacturer must strategically downward distort both output and carbon emission reduction levels. This mechanism characterizes a unique signaling equilibrium in the supply chain, thereby bridging a critical research gap in modeling emission reduction under information asymmetry. (2) Furthermore, this study constructs emission reduction level as a key variable within the signaling framework, moving beyond the conventional reliance on single signals such as output in traditional supply chain signaling research. More importantly, it quantifies how market fluctuations, demand probability, emission reduction capability, and consumer low-carbon preference influence this signaling strategy's viability. The findings provide managers with actionable insights, enabling them to evaluate key factors under market uncertainty and adjust their strategies to manage downstream expectations and coordinate the supply chain proactively.

2 Literature review

The literature review is organized into two primary sections: one focuses on low-carbon supply chains, and the other explores signaling game.

2.1 Low-carbon supply chains

A significant amount of research has been conducted on low-carbon supply chains. Most scholars analyze the supply chain participants' decision-making in reducing carbon emissions under the assumption of symmetric information. [19] Were the first to incorporate carbon emission considerations into operations management models, demonstrating that firms can achieve significant emission reductions without substantial cost increases. By modeling various channel structures, [15] Showed that dual-channel development enhances manufacturer profits while harming retailer interests in the supply chain with limited risk aversion. [20] Compared independent emission abatement by the manufacturer with joint abatement by both supply chain partners, proving that cooperation yields higher returns for both parties. [21] Found that in competitive supply chains, unilateral carbon reduction investment may create positive externalities by increasing all manufacturers' profits, thereby facilitating cooperation in emission reduction technology. [22] Showed that e-commerce platforms can accelerate the low-carbon transition by prioritizing such products, which gives a competitive advantage to manufacturers with strong emission reduction capabilities. [23] Confirmed that in competing supply chains with asymmetric channel structures, consumer green preferences generate positive market effects for both green and conventional supply chains. [24] Found that the application of blockchain technology enhances consumer preferences for both traditional and remanufactured products, thereby facilitating carbon reduction in the supply chain. This setup allows for a clearer examination of the impact of horizontal competition on signaling behavior.

On the other hand, some researchers have also considered the decision-making mechanisms under asymmetric information. Against the backdrop of incomplete demand information, [25] demonstrated that a cap-and-trade mechanism can insulate operational decisions and social welfare from volatile market demand. [11] Examined how green manufacturers signal carbon efficiency information to e-commerce platforms through three signaling strategies: sales volume, carbon emission reduction levels, and a dual-signal approach combining both. The study revealed that using carbon emission reduction levels as a signal increases the separating cost for low efficiency manufacturers. [26] Based on the assumption that consumer low-carbon preference information can be dynamically updated, analyzed the impact of information updating mechanisms and incentive strategies on emission reduction efficiency. The research concluded that an effective information updating mechanism is more conducive to improving overall carbon reduction efficiency than promotional subsidies alone. [27] Compared the performance of the supply chain under build-to-order and build-to-stock modes, finding that information sharing benefits both manufacturers and retailers under both models. While these studies explore the impact of information asymmetry on low-carbon supply chains from various perspectives, none delve deeply into the signaling game between manufacturers and retailers concerning demand information. In contrast, this paper systematically investigates how the manufacturer conveys private demand information to the retailer. It comprehensively characterizes the conditions for the existence of both separating and pooling equilibria and further analyzes the key factors influencing the effectiveness of signaling strategies. Thereby, it extends the research dimension of information structure in the supply chain from the perspective of demand signal transmission.

2.2 Signaling models under information asymmetry

Another category of research investigates signaling models within supply chains under demand information asymmetry. Firstly, scholars have examined situations where downstream firms signal demand information to upstream firms. [28] Investigated how retailers use option contracts to convey demand information to suppliers, finding that high-demand types are more inclined to purchase more options, thereby revealing their true type through the quantity of options. [17] Developed a model with one supplier and two competing retailers, demonstrating that a retailer with private information can signal through order quantities, thereby affecting supply chain coordination efficiency. [29] Further compared signaling strategies based on order quantities in both single channel and dual channel environments. [30] Found that manufacturers can infer market demand conditions based on the retailer's profit margin in a retailer-led supply chain. [31] Proposed that retailers can convey market information to suppliers through ordering commitments in commitment contracts. Secondly, research on upstream firms signaling to downstream firms or consumers is equally noteworthy. [32] Indicated that manufacturers can use slotting fees as promotional tools to signal new product demand information to retailers. [33] Studied the mechanism by which manufacturers use wholesale prices to signal demand information to retailers and analyzed the separating and pooling equilibria within this framework. [34] Explored how manufacturers with private demand information can use guaranteed credit financing contracts to signal to financially constrained retailers. [35] Analyzed the mechanism through which upstream firms improve market demand by disclosing product quality information. [36] Compared the differences in signaling by manufacturers with private demand signals using wholesale prices and buyback prices, finding that buyback prices are a more effective signaling tool than wholesale prices. However, most existing studies analyze signaling issues from only a single dimension. Drawing on [17], who treat output as a demand signal, and [11], who propose carbon emission reduction level as a signal, this paper innovatively examines output and carbon emission reduction levels as dual signals, thereby expanding the research dimension of supply chain signaling theory.

3 Model description

Considering a scenario where manufacturer M1 exclusively produces and sells low-carbon products, while another competitor, manufacturer M2, also produces the same product with the same production cost per unit, denoted as c, supplies it to retailer at w [37]. Retail price for this product is denoted as p. Manufacturer M1 and retailer are involved in a quantity competition, with retailer's costs of operation normalized to zero. Manufacturer M1 initially determines the output Q and also establishes carbon reduction level ε. Upon observing these decisions, retailer sets the order quantity q. Since manufacturer M2 does not make decisions, our analysis only focus on manufacturer M1 (hereinafter referred to as the manufacturer) and retailer.

This paper adopts the following inverse demand function, a specification that has been widely used in the relevant literature [17, 27, 38]. This linear demand function (Equation 1) captures two key market characteristics: First, due to factors such as consumer loyalty and enterprise brand effects, the products sold by the manufacturer and the retailer exhibit a certain degree of substitutability [39]. Second, as consumer preference for low-carbon products continues to grow, product demand is positively correlated with the manufacturer's emission reduction level [40]. Additionally, this functional form helps ensure the existence and tractability of the model's equilibrium solution.

$$p = A_i - Q - \varphi q + \gamma \varepsilon \tag{1}$$

Where A_i represents the base demand, the manufacturer and retailer's competition intensity is represented by φ $(0 < \varphi < 1)$, and a larger φ means more intense competition; γ denotes consumer preference for low-carbon product. All parameters are positive numbers.

Following the modeling approaches of [41, 42], our paper abstracts from fixed costs and models carbon emission reduction costs as a function of the emission reduction level, assuming an increasing marginal cost as the reduction level rises. Specifically, we represent the emission reduction cost using a quadratic function of the emission reduction level, expressed as Equation 2:

$$C(e) = k\frac{\varepsilon^2}{2} \tag{2}$$

k denotes capacity for reducing carbon emissions. A higher value of k indicates a decreased ability of the manufacturer to lower emissions.

Similar to [36], the basic demand for A_i can be high (A_H) or low (A_L) with $A_L < A_H$. The manufacturer knows exactly the actual market demand A_i, $i \in \{H, L\}$, while the retailer doesn't know A_i but only its distribution. The distribution of market demand satisfies $\Pr(A_i = A_H) = \lambda$, $\Pr(A_i = A_L) = 1 - \lambda$, and $0 < \lambda < 1$. The mean value of market demand is $\mu = \lambda A_H + (1 - \lambda) A_L$, with $0 < A_L < \mu < A_H$. The retailer's belief about market demand is A_j , where $j \in \{H, L, N\}$. The retailer's belief about the market demand aligns perfectly with real-world market conditions when $i = j$. N indicates that the retailer cannot know the current market demand state and makes decisions only based on prior beliefs. We employ the superscripts B, S, and P to represent the situations involving symmetric information, separating equilibrium, and pooling equilibrium. As we mentioned earlier, the subscripts i and j indicate the manufacturer's acquisition of market demand type and the retailer's perception of market type. For example, q_{LL}^S represents the order quantity under separating equilibrium, where the manufacturer acquires a low demand and the retailer holds a low-demand expectation.

4 Decision under symmetric information benchmark

Both the manufacturer and the retailer have a clear understanding of the true market demand for products under symmetric information conditions, where $i = j \in \{H, L\}$. The manufacturer initially sets her output Q_{ij}^B and the carbon emission reduction level ϵ_{ij}^B. The retailer then determines his order quantity q_{ij}^B based on the manufacturer's production volume and carbon emission reduction level. When the selling season arrives, the market demand is realized. To obtain the optimal results, we employ backward induction methodology.

Therefore, the retailer's profit maximization problem is given in Equation 3:

$$\pi_{ij}^B\left(q_{ij}^B\right) = \left(A_i - Q_{ij}^B - \phi q_{ij}^B + \gamma \epsilon_{ij}^B - w\right) q_{ij}^B \tag{3}$$

The manufacturer aims to optimize profits at the level given in Equation 4:

$$\Pi_{ij}^B\left(Q_{ij}^B, \epsilon_{ij}^B\right) = (p - c) Q_{ij}^B - \frac{k}{2}\epsilon_{ij}^{B2} \tag{4}$$

The solution is denoted as $Q_{ij}^{B*}, \epsilon_{ij}^{B*}$. The following Lemma 1 describes the optimal decisions of the two parties under information symmetry.

Lemma 1: *On symmetric information benchmark, manufacturer provides a output of* $Q_{ij}^{B*} = \frac{2k(A_i - 2c + w)}{4k - \gamma^2}$ *and a carbon emission reduction level of* $\epsilon_{ij}^{B*} = \frac{A_i\gamma - 2c\gamma + w\gamma}{4k - \gamma^2}$, *obtains an expected profit of* $\Pi_{ij}^B = \frac{(A_i - 2c + w)^2 (4k^2 - \gamma^2)}{2(4k - \gamma^2)^2}$. *The retailer's order quantity is* $q_{ij}^{B*} = \frac{(A_i + 2c - 3w)k + (w - c)\gamma^2}{\phi(4k - \gamma^2)}$ *and the profit is* $\pi_{ij}^B = \frac{[(A_i + 2c - 3w)k + (w - c)\gamma^2]^2}{(4k - \gamma^2)^2 \phi}$.

Lemma 1 systematically reveals the influence of various parameters on supply chain decisions. First, regarding the external operating environment faced by the manufacturer, when market demand increases (higher A_i), competitor wholesale prices rise (higher w), or consumer preference for low-carbon products strengthens (higher γ), the manufacturer not only expands output (Q) but also simultaneously enhance carbon emission reduction levels (ϵ). This indicates that favorable market conditions not only encourage scale expansion but also provide effective incentives for green investment, facilitating the synergistic improvement of economic performance and environmental reputation. Second, in terms of internal operational capabilities, if a company suffers from backward green technology (higher k) or high unit production costs (higher c), both its output and emission reduction levels will be constrained, creating a "dual squeeze" effect that reflects the fundamental constraint of internal efficiency on sustainable development. Finally, the impact of channel competition intensity (ϕ) demonstrates significant asymmetry, the negative effects of intensified competition are entirely borne by the retailer, while the manufacturer's output and emission reduction decisions remain unaffected, highlighting the manufacturer's dominant position in the channel power structure. In summary, companies must strategically integrate considerations of external market trends, internal capability building, and channel relationship management to achieve both economic and environmental objectives in complex environments.

5 The signaling strategies of the manufacturer under asymmetric information

We primarily investigate the separating and pooling equilibria in this section, where the manufacturer uses production quantities and carbon emission reduction levels signaling demand to the retailer while possessing private demand information. For the sake of simplicity, the manufacturer encountering higher market demand are defined as H-type manufacturer; conversely, that facing lower demand is classified as L-type manufacturer.

5.1 Separating equilibrium

Previous analysis examined both parties' decisions under symmetric information. Findings reveal that the retailer tends to set a lower order volume when encountering low market demand. Under conditions of demand information asymmetry, the H-type manufacturer is might pretend to be the L-type manufacturer to persuade the retailer reducing order volume, thereby increasing her own sales quantity. Therefore, in order to maximize her expected profit, the H-type manufacturer is driven to feign a lower market demand (essentially mimicking the L-type manufacturer) to foster the retailer's perception of a low market demand type, consequently, the retailer adjusts its order volume to a lower level accordingly. Conversely, the L-type manufacturer is motivated to distinguish herself from the H-type manufacturer, enabling the retailer to infer her low-demand forecast and set an appropriate low order quantity. As a result, the L-type manufacturer incurs signaling cost in order to differentiate from the H-type manufacturer.

The H-type manufacturer is motivated to mimic the output and carbon emission reduction level established by the L-type manufacturer. Should this strategy prove successful, it would result in the retailer incorrectly perceiving the market demand as low, thereby adjusting his belief $j = L$ accordingly and providing an order quantity appropriate for low market demand, $q\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right)$. Nonetheless, the actual market condition reflects high demand ($i = H$), leading to a high demand under the low order quantity. Given the absence of a reliable communication channel, and foreseeing that the retailer would interpret the demand metrics from manufacturer's measures, the L-type manufacturer would actively reveal accurate market demand information through her output and carbon emission reduction level. Under asymmetric information conditions, the L-type manufacturer achieves her effective signaling at the point specified in Equation 5:

$$\Pi_{LL}^{B}\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right) = MaxE\left[(p-c)Q_{LL}^{S} - \frac{k}{2}{\epsilon_{LL}^{S}}^{2}\right]$$

$$s.t. \quad \Pi_{HL}^{S}\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right) \leq \Pi_{HH}^{B}\left(Q_{HH}^{B*}, \epsilon_{HH}^{B*}\right)$$

$$\Pi_{LH}^{S}\left(Q_{HH}^{B*}, \epsilon_{HH}^{B*}\right) \leq \Pi_{LL}^{B}\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right) \tag{5}$$

In choosing the signaling value $\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right)$, the L-type manufacturer may opt for a value distinct from the symmetric information condition. In an effort to mimic the L-type manufacturer, the H-type manufacturer may adopt the same choice $\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right)$, then the maximum profit it can obtain is $\Pi_{HL}^{S}\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right)$. Conversely, if the H-type manufacturer refrains from the imitation and opts for the production volume and carbon emission reduction level appropriate for high demand $\left(Q_{HH}^{B*}, \epsilon_{HH}^{B*}\right)$, the retailer then would reciprocate with an order quantity corresponding to high demand, resulting in the manufacturer's profit aligning with that under symmetric information conditions $\Pi_{HH}^{B}\left(Q_{HH}^{B*}, \epsilon_{HH}^{B*}\right)$. When $\Pi_{HL}^{S}\left(Q_{LL}^{S}, \epsilon_{LL}^{S}\right)$ does not exceed $\Pi_{HH}^{B}\left(Q_{HH}^{B*}, \epsilon_{HH}^{B*}\right)$, the H-type manufacturer lack motivation to mimic, thereby enabling the establishment of a separating equilibrium under signaling conditions. The separating equilibrium further requires that the L-type manufacturer exhibits no rational motivation to strategically depart from out-of-equilibrium scenario.

Define $\theta = \frac{A_H + w - 2c}{A_L + w - 2c}$, which measures the demand volatility levels. The following Proposition 1 demonstrates that a separating equilibrium exists where the manufacturer employs output and carbon emission reduction level to signal demand, thereby influencing the decisions of the manufacturer and the retailer.

Proposition 1: *When $0 < k \leq 1$, $0 < \gamma < 2\sqrt{k}$ and $1 < \theta < 3$, the most effective separating equilibrium exists for the manufacturer to signal market demand information through output and emission reduction level. 1) The H-type manufacturer's output and carbon emission reduction level equal to those under symmetric information, $\left(Q_{HH}^{B*}, \epsilon_{HH}^{B*}\right)$. 2) The L-type manufacturer's output is lower than that under symmetric information, i.e., $Q_{LL}^{S*} < Q_{LL}^{B*}$. 3) The L-type manufacturer's carbon emission reduction level is lower than that under symmetric information, i.e., $\varepsilon_{LL}^{S*} < \varepsilon_{LL}^{B*}$. 4) According to the L-type manufacturer's output Q_{LL}^{S*} and carbon emission reduction level ε_{LL}^{S*}, the retailer's order quantity is lower than that under symmetric information, i.e., $q_{LL}^{S*} < q_{LL}^{B*}$.*

Proposition 1 reveals that the existence of a separating equilibrium depends not only on the demand volatility θ but is also strictly constrained by the emission reduction cost coefficient k and consumer preference for low-carbon products γ. Specifically, a separating equilibrium holds only when $k \leq 1$ and $0 < \gamma < 2\sqrt{k}$; violation of either condition leads to the collapse of the equilibrium. The condition $k \leq 1$ indicates that the manufacturer possesses sufficient emission reduction efficiency, where unit investment in abatement yields significant market returns, thereby laying the foundation for differentiated signaling. If k is too high ($k > 1$), the marginal cost of emission reduction increases sharply, making it too costly for the L-type manufacturer to signal through emission reduction efforts, thus eliminating its incentive to participate in the signaling game. The parameter γ represents consumers' willingness to pay for low-carbon products, constituting the external pull for emission reduction efforts, while k determines the opportunity cost for the H-type manufacturer to mimic the L-type. The condition $0 < \gamma < 2\sqrt{k}$ essentially defines the balance between market pull and internal capability: when γ does not exceed $2\sqrt{k}$, consumer preference is not strong enough to compel the H-type manufacturer to abandon its advantage in emission reduction, thereby curbing its incentive to mimic and allowing the separating equilibrium to be maintained. Once $\gamma > 2\sqrt{k}$, consumers' willingness to pay is excessively high, while the firm's emission reduction capability fails to keep pace. In this case, the potential benefit for the H-type manufacturer from mimicking the L-type outweighs the cost of concealing its true type, leading to the breakdown of the separating equilibrium.

After satisfying the basic conditions on k and γ, the demand volatility θ further determines the specific form of the separating equilibrium. When $\theta \geq 3$, market volatility is intense, and if the H-type manufacturer mimics the L-type, it would face substantial profit losses. Thus, it maintains its decisions under symmetric information, resulting in a "costless separation." When $1 < \theta < 3$, market fluctuations are moderate, and the H-type manufacturer can achieve net benefits through mimicry, creating an incentive to disguise herself. In this scenario, the L-type manufacturer must downward distort both output and emission reduction levels, bearing a "signaling cost" to effectively deter mimicry and sustain the separating equilibrium. Therefore, managers should dynamically assess the three parameters k, γ, and θ. If consumers' green preference significantly exceeds the critical threshold of the firm's emission reduction efficiency (i.e., $\gamma > 2\sqrt{k}$), they should be alert to the risk of signaling strategy failure and consider switching to more credible certification mechanisms, such as third-party certifications or technology patents, to effectively convey their private information.

The inference effect is a core economic consequence arising from information asymmetry in signaling games [43]. It occurs when the receiver successfully deduces the sender's private information based on strategically distorted decisions, then adjusts its strategy, thereby influencing the overall welfare of both parties. By comparing the profit levels of the manufacturer and retailer under symmetric information and separating equilibrium, we analyze the impact of the inference effect on supply chain members, as detailed in Proposition 2.

Proposition 2: *The inference effect reduces the profits of both supply chain members: 1) The L-type manufacturer's profit is lower than that under symmetric information, i.e.,* $\Pi^S_{LL}\left(Q^{S*}_{LL}, \epsilon^{S*}_{LL}\right) < \Pi^B_{LL}\left(Q^{B*}_{LL}, \epsilon^{B*}_{LL}\right)$. *2) The retailer's profit is also lower than that under symmetric information, i.e.,* $\pi^S_{LL}\left(q^{S*}_{LL}\right) < \pi^B_{LL}\left(q^{B*}_{LL}\right)$.

Proposition 2 reveals the welfare loss imposed on both parties due to information asymmetry through the inference effect. Specifically, to achieve effective separation, the L-type manufacturer must reduce her output and carbon emission reduction levels below the optimal values under symmetric information. Although this strategy successfully conveys the true low-demand signal, it leads to deviations from the optimal production and emission reduction paths, thereby decreasing sales revenue and profit. For the retailer, upon observing the low signal from the L-type manufacturer, he can accurately infer the low market demand and adjust his order quantity to a level lower than that under symmetric information. Although this response is rational in a separating equilibrium, the retailer's decision is based on distorted initial signals, and thus his final profit still falls short of the optimum under symmetric information. As a result, the inference effect causes a simultaneous loss of profit for both supply chain parties, creating a typical "lose-lose" outcome.

5.2 Pooling equilibrium

We continue to explore the pooling equilibrium, where different types of manufacturers "pool" together by setting the same output and emission reduction strategies. Consequently, the retailer cannot identify the signal and still maintains his prior belief. This is because the H-type manufacturer successfully mimics the L-type manufacturer by choosing the same production quantities and emission reduction levels. The retailer can only make decisions align with average market expectations μ. In the pooling equilibrium, manufacturers tend to weaken the retailer's perception of high market demand, which helps them boost their own competitiveness and maximize their expected profit. Specifically, when both H-type and L-type manufacturers adopt similar production scales and emission reduction levels, the retailer cannot update his perception of market demand, leading him to assume a low-demand scenario. However, deviations from these aligned decisions, particularly in production quantities and emission reduction measures, signal a high-demand market to the retailer.

Therefore, to achieve a pooling equilibrium, the manufacturer's optimal strategy must meet the conditions given in Equations 6, 7:

$$\Pi^P_{LN}\left(Q^P_{LN}, \epsilon^P_{LN}\right) = MaxE\left[(p-c)Q^P_{LN} - \frac{k}{2}{\epsilon^P_{LN}}^2\right]$$

$$\Pi^P_{HN}\left(Q^P_{HN}, \epsilon^P_{HN}\right) = MaxE\left[(p-c)Q^P_{HN} - \frac{k}{2}{\epsilon^P_{HN}}^2\right]$$

$$\Pi^B_{HH}\left(Q^{B*}_{LL}, \varepsilon^{B*}_{LL}\right) \le \Pi^P_{HN}\left(Q^P_{HN}, \epsilon^P_{HN}\right)$$

$$\Pi^P_{LH}\left(Q^{P*}_{LH}, \varepsilon^{P*}_{LH}\right) \le \Pi^P_{LN}\left(Q^P_{LN}, \epsilon^P_{LN}\right) \tag{6}$$

where

$$q^{P*}_{LN}\left(Q^P_{LN}, \epsilon^P_{LN}\right) = arg\ max\left[\left(\mu - Q^P_{LN} - \phi q^P_{LN} + \gamma\epsilon^P_{LN} - w\right)q^P_{LN}\right]$$

$$q^{P*}_{HN}\left(Q^P_{HN}, \epsilon^P_{HN}\right) = arg\ max\left[\left(\mu - Q^P_{HN} - \phi q^P_{HN} + \gamma\epsilon^P_{HN} - w\right)q^P_{HN}\right] \tag{7}$$

When the manufacturer deviates from the pooling equilibrium, opting for either $\left(Q^{P*}_{LH}, \varepsilon^{P*}_{LH}\right)$ or $\left(Q^{P*}_{HH}, \varepsilon^{P*}_{HH}\right)$, the retailer interprets the market demand to be high, which leads to Equation 8:

$$q^{P*}_{LH}\left(Q^P_{LH}, \epsilon^P_{LH}\right) = arg\ max\left[\left(A_H - Q^P_{LH} - \phi q^P_{LH} + \gamma\epsilon^P_{LH} - w\right)q^P_{LH}\right]$$

$$q^{P*}_{HH}\left(Q^P_{HH}, \epsilon^P_{HH}\right) = arg\ max\left[\left(A_H - Q^P_{HH} - \phi q^P_{HH} + \gamma\epsilon^P_{HH} - w\right)q^P_{HH}\right] \tag{8}$$

Proposition 3 describes the existence of a pooling equilibrium through which the manufacturer signals demand using production quantities and carbon emission reduction levels, and characterizes the optimal decisions of the manufacturer and retailer within this equilibrium.

Proposition 3: *When* $0 < \gamma < 2$, $\frac{\sqrt{2(2+\gamma^4)}-2}{\gamma^2} < k < 1$ *and* $1 < \theta \le \frac{-8k-\gamma^2(-3+\lambda)+k^2\gamma^2(-1+\lambda)}{-8k-\gamma^2(-4+\lambda)+k^2\gamma^2(-2+\lambda)}$, *the most effective pooling equilibrium exists for the manufacturer to signal market demand information through output and emission reduction level. 1) The L-type manufacturer's output is lower than that under symmetric information, i.e.,* $Q^{P*}_{LN} < Q^{B*}_{LL}$. *2) The L-type manufacturer's emission reduction level is lower than that under symmetric information, i.e.,* $\varepsilon^{P*}_{LN} < \epsilon^{B*}_{LL}$. *3) According to the L-type manufacturer's output and emission reduction level, the retailer's order quantity is higher than that under symmetric information, i.e.,* $q^{P*}_{LN} > q^{B*}_{LL}$.

According to Proposition 3, manufacturer's choices in production and carbon reduction are shaped by our main factors: the extent of market demand variability θ, the retailer's prior probability λ, capacity for reducing carbon emissions k, and consumer preference for low-carbon products γ. Here, we focus on the impact of demand volatility. When $1 < \theta \le \frac{-8k-\gamma^2(-3+\lambda)+k^2\gamma^2(-1+\lambda)}{-8k-\gamma^2(-4+\lambda)+k^2\gamma^2(-2+\lambda)}$, compared to symmetric information, the manufacturer has to choose a downward distorted production quantities and carbon emission reduction levels to achieve a pooling equilibrium. Since the manufacturer sets the same strategies, the retailer cannot update his market belief at this time and makes decisions based on prior information, resulting in a correspondingly higher order quantity than the order quantity level under low demand with symmetric information. In a low-demand market scenario, the manufacturer reduces her production quantities and carbon emission measures to achieve the pooling equilibrium, but since the retailer makes decisions based on his prior concept of the market, the order quantity is relatively high; while in a high-demand market condition, the manufacturer reduces pooling production and carbon emission reduction levels, and the retailer, basing decisions on prior concept of the market, sets a relatively lower order quantity. Proposition 4 is established through the analysis of the manufacturer and retailer's profitability in this pooling equilibrium.

Proposition 4: *In the pooling equilibrium, 1) The L-type manufacturer's profit is lower than that under symmetric information, i.e.,* $\Pi_{LN}^{P}\left(Q_{LN}^{P*},\epsilon_{LN}^{P*}\right) < \Pi_{LL}^{B}\left(Q_{LL}^{B*},\varepsilon_{LL}^{B*}\right)$. *2) The retailer's profit is higher than that under symmetric information, i.e.,* $\pi_{LN}^{P}\left(q_{LN}^{P*}\right) > \pi_{LL}^{B}\left(q_{LL}^{B*}\right)$.

Proposition 4 indicates when the market is in a low-demand state, both the production and emission reduction levels decrease to achieve the pooling equilibrium. The retailer makes decisions based on their prior concept of the market, resulting in a relatively higher order quantity. Consequently, the manufacturer's profit is correspondingly reduced. This reduction in profit represents the extra expense the manufacturer must incur to get this pooling equilibrium. As can be seen from Cao and Chen [43], when there is information asymmetry, it is always disadvantageous for the manufacturer to convey demand signals in any manner. For the retailer, increasing order quantities based on prior decisions is advantageous.

5.3 Manufacturer's signal strategies

In the previous section, we found that when there is asymmetric information about demand, the L-type manufacturer can signal demand market information to the retailer using both separating and pooling equilibrium strategies, we also obtained the ranges for these two equilibria. So, which strategy should the manufacturer choose to signal demand? Proposition 5 describes the signal strategies of the manufacturer under different circumstances.

Proposition 5: When $0 < \gamma < \sqrt{3} - 1$, $\sqrt{\frac{3}{2} + \frac{1}{\gamma^4}} - \frac{1}{\gamma^2} \le k \le \frac{\gamma}{2}$ and $1 < \theta \le \frac{1+\lambda}{\lambda}$, the manufacturer chooses a pooling equilibrium strategy; otherwise, the manufacturer selects a separating equilibrium strategy.

Proposition 5 indicates that the manufacturer's signaling strategy is dictated by factors such as market demand volatility θ, the prior probability of market demand λ, capacity for reducing carbon emissions k, as well as consumer preferences for low-carbon products γ. We explore the influence of each factor on the signaling strategy as follows:

Firstly, the manufacturer's signaling strategy is affected by the market demand volatility θ. When demand volatility θ is small, manufacturer tends to prefer a pooling equilibrium for signaling. This is because, in a stable market environment, the manufacturer faces similar demand conditions, and the cost and complexity of signal are relatively low. A pooling equilibrium allows the manufacturer to send uniform signals, reducing signaling costs and minimizing market confusion, thereby efficiently coordinating market behavior. In contrast, in markets with high demand fluctuation, the manufacturer is more inclined to adopt a separating equilibrium strategy. In such environments, the uncertainty of market demand increases, and a separating equilibrium enables the manufacturer to send distinct signals based on her specific demand conditions and market judgments. This approach more accurately reflects true market information, enhances the credibility of signals, and allows market participants to better adjust her production and decision-making based on the signals. Although a separating equilibrium may incur higher signal and market coordination costs, it provides greater flexibility and adaptability in unstable market conditions, enabling the manufacturer to respond more effectively to sharp demand fluctuations.

Secondly, we find that demand volatility θ impacts the retailer's prior probability of market demand λ, which in turn affects the manufacturer's signaling strategy. When the proportion λ of the high-demand market type is large, implying a favorable market demand, the threshold for market demand variability decreases. The manufacturer has a smaller range for choosing a pooling equilibrium signaling strategy and a larger range for selecting a separating equilibrium signaling strategy. This is consistent with supply chain practices. Under optimistic expectations, the retailer actively adjusts inventory and procurement strategies. The manufacturer sends more accurate and differentiated signals regarding output and carbon reduction levels, better reflecting the current market demand situation. This strategy enhances the accuracy of signals, enabling the retailer to more accurately predict market dynamics and make more reasonable procurement decisions, thereby preventing inventory surplus or deficits. However, when the retailer holds a pessimistic view of market demand, the manufacturer tends to choose a pooling equilibrium to send signals. Under pessimistic expectations, the retailer may adopt a conservative procurement strategy. By sending consistent signals, such as maintaining the same output and carbon reduction levels, the manufacturer can reduce information complexity and alleviate the retailer's concerns about market demand uncertainty.

Thirdly, a manufacturer with weaker carbon emission reduction capabilities (as indicated by a larger k value) is more likely to adopt a separating equilibrium to effectively send demand signals. Conversely, the stronger its carbon emission reduction capability (as indicated by a smaller k value), the more inclined it is to use a pooling equilibrium to signal. Specifically, a manufacturer with stronger carbon reduction capability tends to adopt a pooling equilibrium strategy to signal demand for low-carbon products. This approach allows it to demonstrate industry consensus and leadership, reduce market information confusion and transmission costs, and enhance consumer and retailer confidence in low-carbon products, thereby promoting overall market stability. However, a manufacturer with weaker carbon emission reduction capability is more likely to use a separating equilibrium strategy to send demand signals. This strategy enables it to adjust production and carbon reduction levels more precisely based on its actual capabilities and market feedback, avoiding signal rigidity and missed market opportunities due to capability limitations. Additionally, separating equilibrium provides flexibility for a manufacturer with weaker capabilities, allowing it to attract specific consumers or retailers through differentiated signals and enhance its competitiveness in a highly competitive market.

Finally, when consumers pay little attention to whether a product is low-carbon as indicated by a smaller γ value), the manufacturer may deem sending differentiated signals meaningless. Consumers are unlikely to make significant purchasing distinctions based on such signals. In this case, the manufacturer prefers to send uniform signals by maintaining consistent production levels and carbon reduction efforts. This approach reduces signaling costs and avoids confusion from signal differences. Conversely, when consumers strongly prefer low-carbon products (i.e., when they heavily emphasize the low-carbon characteristics), the manufacturer finds sending differentiated signals more meaningful. The levels of production and carbon reduction directly reflect the manufacturer's production capacity or market positioning for low-carbon products. By sending differentiated signals, the manufacturer can more accurately signal its market information and attract specific consumer types. This allows for better market segmentation and product positioning.

6 Extensions

6.1 The impact of government subsidies on the supply chain

To promote green and low-carbon development, governments worldwide commonly provide subsidies to manufacturers of low-carbon products to encourage environmentally friendly production [44]. In this context, this study extends the analysis to incorporate government subsidies and examines their impact on decision-making in a low-carbon supply chain under demand information asymmetry. Following the modeling approach of Yang and Xiao [45] and Dai et al. [46] for government subsidies, the unit product subsidy is defined as $\delta\epsilon$, where $\delta > 0$ represents the unit product subsidy coefficient. We use the superscript G to denote government subsidies, then the profit functions of the retailer are given in Equation 9:

$$\pi_{ij}^{G}\left(q_{ij}^{G}\right) = \left(A_i - Q_{ij}^{G} - \phi q_{ij}^{G} + \gamma\epsilon_{ij}^{G} - w\right)q_{ij}^{G} \tag{9}$$

and the manufacturer's profit can be expressed as Equation 10:

$$\Pi_{ij}^{G}\left(Q_{ij}^{G},\epsilon_{ij}^{G}\right) = \left(p - c + \delta\epsilon_{ij}^{G}\right)Q_{ij}^{G} - \frac{k}{2}\epsilon_{ij}^{G2} \tag{10}$$

Based on the above setup, this study focuses on the scenario where government subsidies and demand information asymmetry coexist, analyzing how a L-type manufacturer adjusts her output and emission reduction levels to convey private demand information to the retailer. By constructing and solving a corresponding signaling game model, we derive Proposition 6, which systematically reveals the impact of government subsidies on the manufacturer's signaling strategy and the resulting equilibrium outcomes.

Proposition 6: *When government subsidies are considered: 1) Under the conditions $k > \delta^2$, $0 < \gamma < 2\sqrt{k} - 2\delta$ and $1 < \theta \leq 3$, the most effective separating equilibrium exists where the manufacturer uses output and emission reduction levels to convey market demand information. In this case, both the output and carbon emission reduction level of the L-type manufacturer are higher than those without subsidies, and the retailer's order quantity is also higher than its value without subsidies. 2) Under the conditions $1 < \theta < \frac{\lambda^2-2\lambda-3}{\lambda^2-4\lambda-1}$, the most effective pooling equilibrium exists where the manufacturer uses output and emission reduction levels to convey market demand information. In this case, both the output and carbon emission reduction level of the L-type manufacturer are higher than those without subsidies, and the retailer's order quantity is also higher than its value without subsidies. 3) Government subsidies influence the L-type manufacturer's signaling strategies.*

By comparing Proposition 6 with Propositions 1, 3, it can be observed that the introduction of government subsidies significantly alters the existence conditions and manifestations of supply chain signaling equilibria. Compared to the requirement of $0 < k < 1$ for the separating equilibrium in Proposition 1, Proposition 6 allows the emission reduction cost coefficient to fall within a higher range ($k > \delta^2$) under the subsidy scenario, indicating that the subsidy policy effectively alleviates the constraints faced by the manufacturer due to insufficient emission reduction technology, thereby broadening the applicability of the separating equilibrium. In terms of consumer preferences, the condition in Proposition 6 ($0 < \gamma < 2\sqrt{k} - 2\delta$) is more stringent than the condition $0 < \gamma < 2\sqrt{k} - 2\delta$ in Proposition 1, reflecting that while subsidies enhance emission reduction capabilities, they also impose higher requirements on market green awareness. The introduction of government subsidies also significantly changes the existence conditions and performance of the pooling equilibrium. Proposition 3 shows that in the absence of subsidies, the existence of a pooling equilibrium requires the simultaneous satisfaction of strict constraints on emission reduction efficiency, consumer preferences, and channel competition intensity. In contrast, Proposition 6 simplifies the existence conditions of the pooling equilibrium under the subsidy scenario to primarily depend on the degree of demand fluctuation. This shift demonstrates that government subsidies, by altering the revenue structure of the manufacturer, reduce the sensitivity of the pooling equilibrium to other environmental parameters, thereby maintaining the effectiveness of signal transmission under more relaxed conditions.

More importantly, under both equilibria in Proposition 6, the L-type manufacturer achieves higher output and emission reduction levels compared to the separating equilibrium without subsidies, while retailer order quantities also increase simultaneously. This indicates that government subsidies not only incentivize the signal sender but also benefit the signal receiver through demand expansion effects. By comparing the performance of supply chain members under symmetric and asymmetric information, we derive Proposition 7.

Proposition 7: *When government subsidies are considered, the performance of all supply chain members improves.*

For the manufacturer, the subsidy directly reduces her unit emission reduction cost, enabling it to achieve higher marginal profit at any given emission reduction level. This incentivizes the manufacturer to simultaneously increase both output and carbon emission reduction levels. The higher emission reduction level enhances the green differentiation advantage of her products, helping to attract more consumers in the end market. The expansion of sales volume and the increase in per-unit profit margin together drive a significant rise in the manufacturer's profit. For the retailer, the performance improvement stems from

TABLE 1 Optimal decision and profit levels for the supply chain under different wholesale price.

Wholesale price / Decision and profit	w = 3	w = 4	w = 5	w = 6	w = 7	w = 8	w = 9	w = 10
Q_{LL}^{B*}	56	57.14	58.29	59.43	60.57	61.71	62.86	64
ε_{LL}^{B*}	42	42.86	43.71	44.57	45.43	46.29	47.14	48
q_{LL}^{B*}	54	53.14	52.29	51.43	50.57	49.71	48.86	48
$\Pi_{LL}^{B}(Q_{LL}^{B*},\varepsilon_{LL}^{B*})$	686	714.29	743.14	772.57	802.57	833.14	864.29	896
$\pi_{LL}^{B}(q_{LL}^{B*})$	1,458	1,412.08	1,366.9	1,322.45	1,278.73	1,235.76	1,193.51	1,152
Q_{LL}^{S*}	53.81	54.41	55.01	55.61	56.22	56.82	57.43	58.04
ϵ_{LL}^{S*}	40.36	40.81	41.26	41.71	42.16	42.62	43.07	43.53
q_{LL}^{S*}	53.73	52.80	51.88	50.95	50.03	49.10	48.18	47.26
$\Pi_{LL}^{S}(Q_{LL}^{S*},\epsilon_{LL}^{S*})$	684.95	712.65	740.79	769.38	798.42	827.91	857.85	888.23
$\pi_{LL}^{S}(q_{LL}^{S*})$	1,443.24	1,393.97	1,345.56	1,298.02	1,251.35	1,205.54	1,160.6	1,116.52

positive market externalities. The manufacturer's enhanced emission reduction level, driven by the subsidy, boosts the overall appeal and competitiveness of green products in its channel. Facing increased demand, the retailer optimally responds by raising its order quantity from competing manufacturers. The growth in sales volume naturally leads to higher profit for the retailer. Under both symmetric and asymmetric demand information scenarios, both the manufacturer and the retailer can achieve Pareto improvements in performance. This underscores the vital role of government subsidies in stimulating market vitality and advancing the green transition.

6.2 The impact of wholesale price on the supply chain

In the above model, the wholesale price w of the competitive manufacturer M2 is set as an exogenous variable. Given that changes in this price may influence the competitive dynamics between the manufacturer and the retailer, this section further investigates the mechanism through which exogenous wholesale price variations affect the decisions and profits of supply chain members. Following the analytical approach of Wu et al. [47] and adopting the parameter settings from Wang et al. [27], with $A_H = 140$, $A_i = A_L = 50$, c = 2 , k = 1, γ = 1.5, and $\phi = 0.5$, we calculate the decision variables and corresponding profits of the manufacturer and retailer under different wholesale price levels. The detailed numerical results are presented in Table 1.

Based on the results in Table 1, as the wholesale price w set by competing manufacturer M2 increases, the retailer's order quantity from M2 gradually decreases, while the manufacturer's output and carbon emission reduction levels correspondingly rise. This change leads to a progressive decline in the retailer's profit and a continuous increase in the manufacturer's profit, indicating that higher wholesale prices place the retailer at a relatively disadvantaged position in supply chain competition.

Similar trends remain valid under asymmetric demand information. As w increases, the range of existence for both separating and pooling equilibria narrows. Taking the separating equilibrium as an example, the manufacturer still needs to downwardly distort output and carbon emission reduction levels to convey demand information to the retailer. With the rise in w, the degree of distortion required for effective signaling deepens. However, since the output expansion effect brought by the wholesale price increase is more substantial, the competitor's wholesale price hike still exerts an overall positive impact on the manufacturer. For the retailer, after inferring the low-demand signal sent by the manufacturer, his ordering willingness further weakens. Meanwhile, the upstream manufacturer M2 raises the wholesale price, and under this dual effect, the retailer's order quantity shrinks further, leading to a continuous decline in profit. It is worth noting that although the manufacturer's output consistently exceeds the retailer's order quantity, the manufacturer bears significant carbon emission reduction costs, resulting in the retailer's profit being higher than the manufacturer's profit.

7 Numerical analysis

7.1 Equilibrium decisions and profit levels in the supply chain

Based on Wang et al. [27], we numerically simulate how demand volatility affects the decisions and profit levels of supply chain members. The parameter values are: $A_i = A_L = 50$, c = 2 , w = 5, k = 1 , $\gamma = 1.5$, and $\phi = 0.5$.

Figure 1a presents the manufacturer's output decisions under symmetric demand information and separating equilibrium,

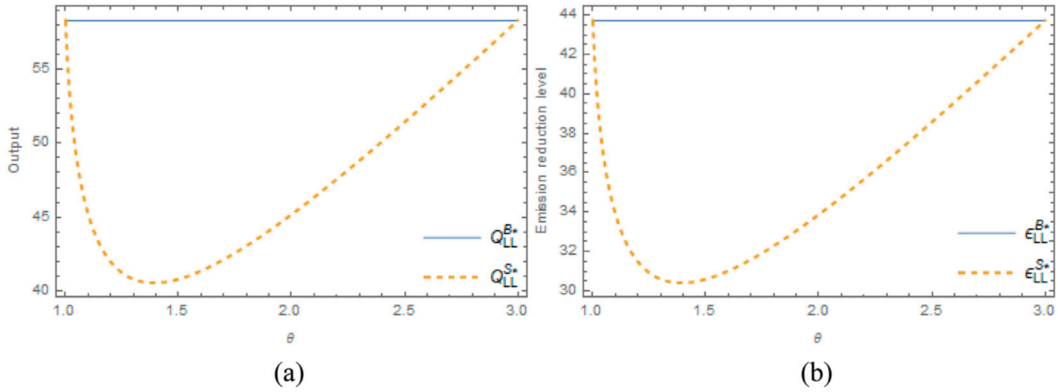

FIGURE 1
Impact of θ on the manufacturer's decisions. **(a)** Output **(b)** Emission reduction levels.

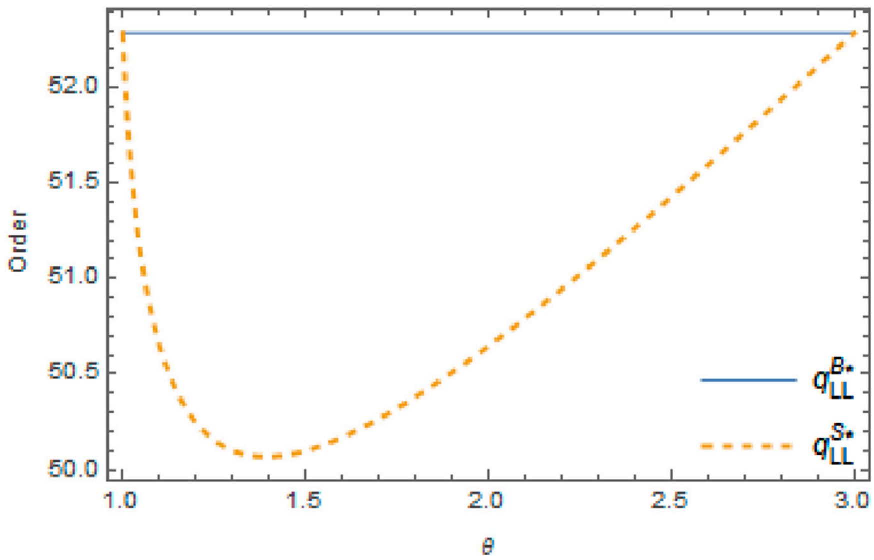

FIGURE 2
Impact of θ on the retailer's decisions.

while Figure 1b displays the corresponding carbon emission reduction levels under these two scenarios. Under symmetric information, the manufacturer's decisions remain unaffected by demand volatility. However, in environments with asymmetric information and mild market fluctuations, the L-type manufacturer must downwardly distort both output and carbon emission reduction levels below her optimal values under symmetric information to achieve effective signaling, thus resulting in lower values under the separating equilibrium. Similarly, the retailer's decisions are also immune to demand volatility under symmetric information, whereas under asymmetric information with small market fluctuations, the retailer infers actual market conditions by observing the manufacturer's signals and formulates ordering strategies accordingly. As shown in Figure 2, the retailer's order quantity under such asymmetric information is consistently lower than the level observed under symmetric information.

Since the decisions of both the manufacturer and the retailer under asymmetric information are lower than those under symmetric information, their profits are accordingly reduced. As shown in Figure 3, under symmetric information, the profits of both the manufacturer and the retailer are independent of the demand volatility θ; under asymmetric information, however, their profits are highly sensitive to changes in θ, and the profit level under the separating equilibrium is significantly lower than that under the symmetric information scenario.

7.2 Factors influencing signaling strategies

We explore how critical parameters (θ, λ, k and γ) influence the manufacturer's signaling strategy across various scenarios. Similar to [17], these parameters are specified as follows: $A_H = 160$,

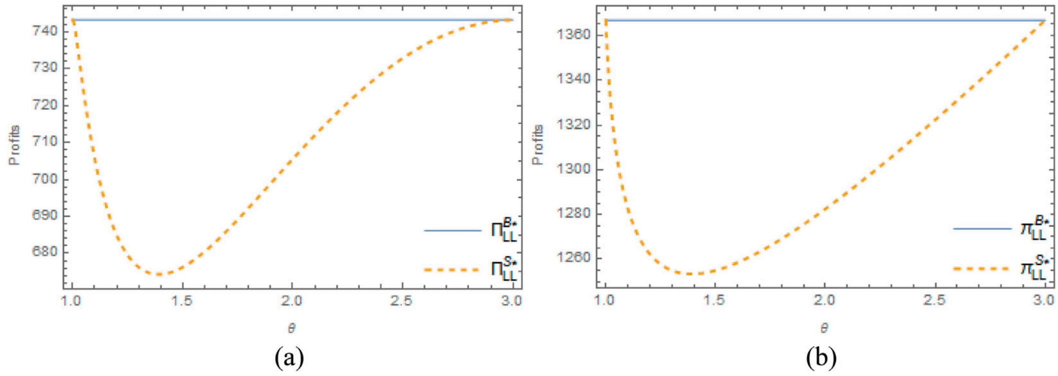

FIGURE 3
Impact of θ on the profits of supply chain members. **(a)** Manufacturer **(b)** Retailer.

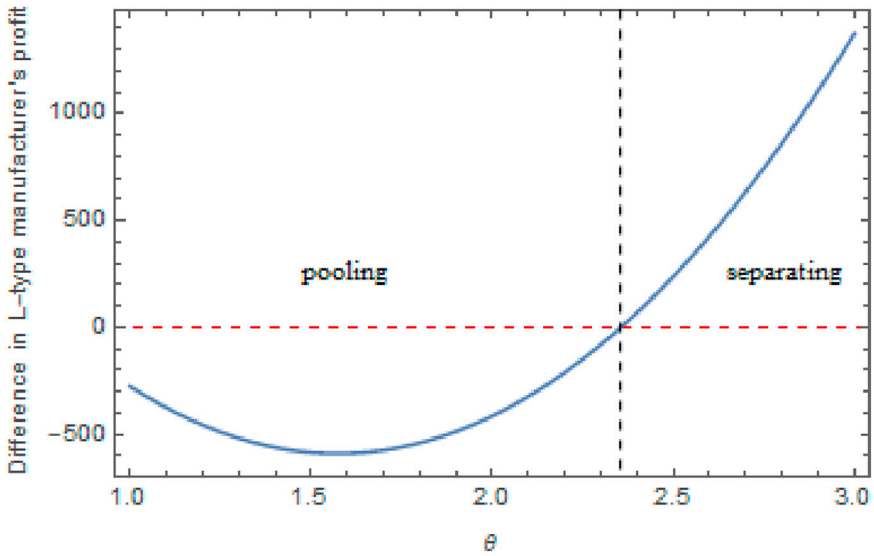

FIGURE 4
Impact of θ on manufacturer's signaling strategy.

$A_L = 50$, c = 2 and w = 5, ensuring non-negative decision variables and optimal solutions for both separating and pooling equilibria.

We analyze the influence of key parameters on the manufacturer's signaling strategy by comparing her profit levels under separating and pooling equilibria. The parameter values are set with reference to Wang et al. [27]. When examining the effect of different parameters, we control for the remaining variables as follows: for θ, we set $\gamma = 0.6$, $k = 0.28$, and $\lambda = 0.8$; for λ, we set $\gamma = 0.6$, $k = 0.28$, and $\theta = 2.5$; for k, we set $\gamma = 0.6$, $\lambda = 0.5$, and $\theta = 2.5$; and for γ, we set $k = 0.28$, $\lambda = 0.5$ and $\theta = 1.5$. In the figures, the vertical axis shows the profit difference between the L-type manufacturer between the separating equilibrium and the pooling equilibrium.

Figure 4 illustrates how market demand volatility influences the manufacturer's signaling strategy. When market demand fluctuates slightly, the manufacturer tends to prefer a pooling equilibrium for signaling. In contrast, in markets with significant demand volatility, the manufacturer is more inclined to adopt a separating equilibrium strategy. A pooling equilibrium is advantageous in stable markets as it simplifies information processing and enables quicker market responses to signals. Conversely, while a separating equilibrium increases information complexity, it provides richer and more precise information in volatile markets, thereby enhancing overall market efficiency and coordination. Figure 5 demonstrates that if the retailer is optimistic about the consumer demand for low-carbon products (i.e., when λ is large), the manufacturer is more likely to choose a separating equilibrium to send signals. However, if the retailer has a negative outlook on market demand (i.e., when λ is small), the manufacturer may be more likely to opt for a pooling equilibrium to simplify information and alleviate the retailer's concerns about demand uncertainty.

Figures 6, 7 show how carbon emission reduction capability and consumers preference for low-carbon product

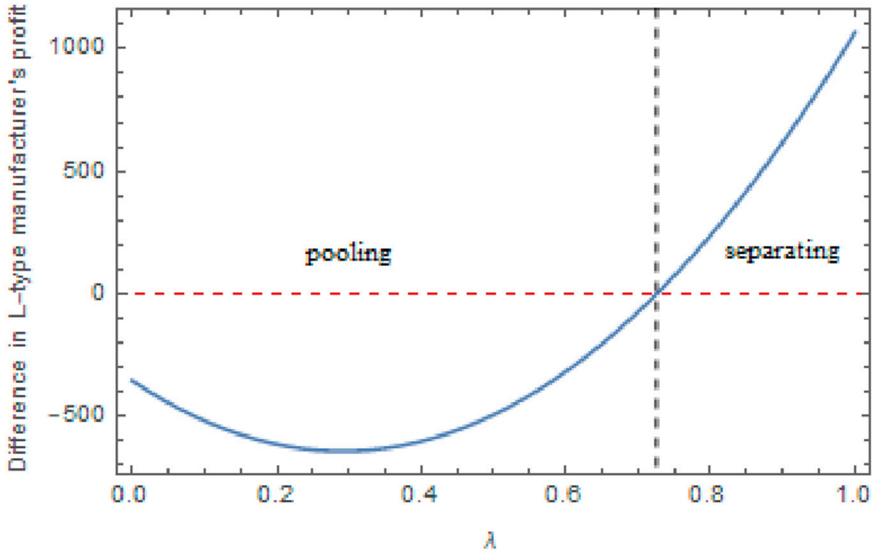

FIGURE 5
Impact of λ on manufacturer's signaling strategy.

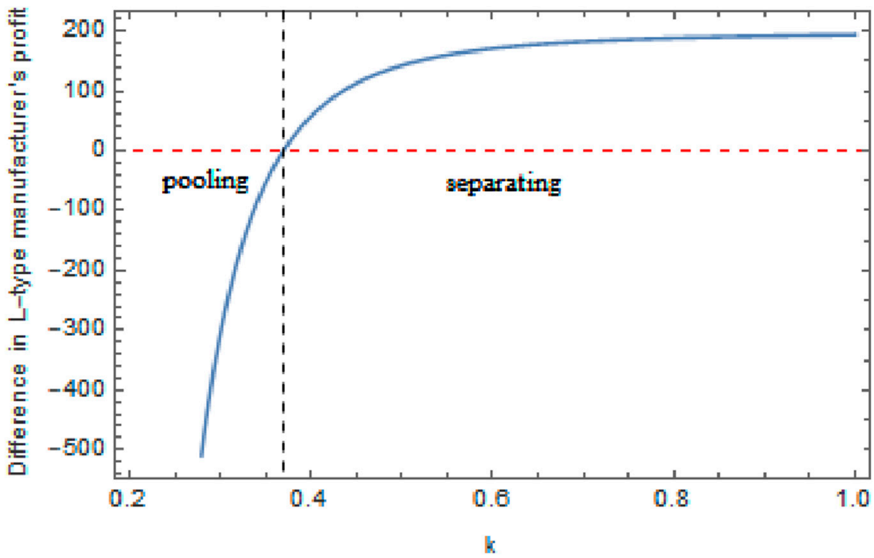

FIGURE 6
Impact of k on manufacturer's signaling strategy.

affect the manufacturer's signaling methods within the supply chain. Figure 6 indicates that a manufacturer with stronger carbon emission reduction capabilities prefers employing a pooling equilibrium to send demand signals for low-carbon products, while one with weaker capabilities prefers a separating equilibrium. As the consumers preference coefficient for low-carbon product decreases, the manufacturer tends to adopt a pooling equilibrium, as illustrated in Figure 7; conversely, as this coefficient increases, the manufacturer tends to adopt a separating equilibrium for signaling demand.

8 Conclusion

Low-carbon supply chains have become a key pathway for companies to achieve sustainable development and enhance their market competitiveness within the global transition toward low-carbon practices. However, the issue of demand information asymmetry is prevalent and has a profound impact on the smooth functioning and harmonious collaboration within the supply chain. This study examines the supply chain, which includes a manufacturer that produces and sells its own low-carbon products and a retailer focused on acquiring low-carbon

10.3389/fphy.2025.1686006

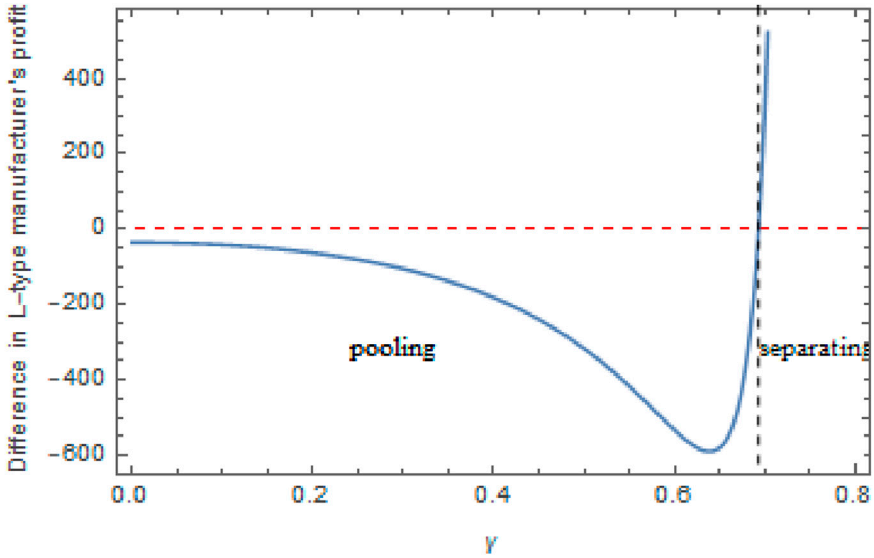

FIGURE 7
Impact of γ on manufacturer's signaling strategy.

products from other upstream manufacturers. Additionally, it considers the separating and pooling equilibria, where this manufacturer holds private demand signals and conveys these signals to the retailer through production quantities and carbon emission reduction levels. We further examine how the manufacturer's signaling strategies are depended on elements such as demand volatility, the retailer's prior probability, its capacity for reducing emissions, and consumer preference for low-carbon products.

Our research findings indicate that the manufacturer signals market demand by downwardly distorting production quantities and emission reduction levels. Signaling is always disadvantageous for the manufacturer. Retailer's interests are compromised under the separating equilibrium but benefit under the pooling equilibrium. In our numerical analysis, we observed that when demand variation is minimal, the manufacturer tends to choose the pooling equilibrium strategy. By sending consistent signals, she reduces the cost of information transmission and promote market coordination and stability. When market demand volatility is high, the manufacturer tends to adopt the separating equilibrium strategy. By sending differentiated signals, she can better reflect changes in market demand and enhance market adaptability and flexibility. Retailer's optimistic or pessimistic expectations about market demand also indirectly influence manufacturer's signaling strategy choices. When retailer is optimistic, manufacturer is inclined to adopt the separating equilibrium to improve signal clarity. However, when retailer is pessimistic, manufacturer opts for the pooling equilibrium strategy to reduce the risk of market confusion. The manufacturer's carbon emissions reduction capabilities also significantly impact her signaling strategies. The manufacturer with strong carbon emission reduction capabilities is more inclined to signal demand through the pooling equilibrium, demonstrating industry consensus and leadership. In contrast, manufacturer with weaker capabilities opts for the separating equilibrium strategy, flexibly adjusting signals to reflect her capabilities and demands. Consumers' preferences further influence manufacturer's signaling decisions. When there is a decline in consumer demand for low-carbon product, the manufacturer tends to adopt the pooling equilibrium strategy to reduce the complexity of signaling. However, when consumer preferences are high, the manufacturer chooses the separating equilibrium strategy to precisely signal demand and attract specific consumer groups.

This study advances the understanding of low-carbon supply chain management in several key dimensions: (1) While existing research has primarily focused on carbon reduction issues where participants share common information about demand markets, it neglects how the manufacturer producing low-carbon products communicate demand signals and her impact mechanisms under demand information asymmetry. This study fills this research gap by thoroughly examining how manufacturers achieve effective communication through signaling strategies under information asymmetry, offering new theoretical perspectives for the supply chain management. (2) Existing signaling literature has largely focused on traditional supply chain environments with limited systematic attention to low-carbon issues. This paper innovatively constructs a signaling model that incorporates carbon reduction levels. Compared to existing literature, this model offers greater integration and practical relevance, more comprehensively capturing the complex interrelations in low-carbon supply chains.

Finally, this paper identifies several limitations of the current model and suggests corresponding directions for future research. First, in terms of model specification, this study employs a linear demand function and does not account for fixed costs. Future research could introduce nonlinear demand functions and incorporate fixed cost structures to enhance the model's realism and explanatory power. Second, to focus on the vertical signaling mechanism between the manufacturer and the retailer, the wholesale price of the competing manufacturer is assumed to be exogenously given. Subsequent studies could endogenize the pricing behavior of the competing manufacturer to explore the impact of horizontal signaling interactions between manufacturers on equilibrium outcomes. Third, this study concentrates on the dual-signal scenario involving output and carbon emission reduction levels, while in reality, firms may employ various signaling tools such as pricing and third-party certifications. Therefore, systematically comparing the effectiveness and applicable conditions of different signaling mechanisms represents an important direction for future research. Lastly, this paper assumes that the manufacturer possesses complete demand information, which differs from the real world scenario where firms obtain probabilistic forecasts through market research. Future work could extend the information structure to incorporate prediction distributions with varying levels of accuracy, thereby exploring the equilibrium properties of signaling within a more generalized informational framework.

Data availability statement

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

Author contributions

SX: Writing – review and editing, Writing – original draft, Software, Formal Analysis, Conceptualization, Data curation. JX: Methodology, Validation, Investigation, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphy.2025.1686006/full#supplementary-material

References

1. Rao C, Gao M, Wen J, Goh M. Multi-attribute group decision making method with dual comprehensive clouds under information environment of dual uncertain Z-numbers. *Inf Sci* (2022) 602:106–27. doi:10.1016/j.ins.2022.04.031

2. Ipcc (2023). AR6 synthesis report: climate change 2023.

3. Lyu R, Zhang C, Li Z, Li Y. Manufacturers' integrated strategies for emission reduction and recycling: the role of government regulations. *Comput Ind Eng* (2022) 163:107769. doi:10.1016/j.cie.2021.107769

4. Toptal A, Çetinkaya B. How supply chain coordination affects the environment: a carbon footprint perspective. *Ann Operations Res* (2017) 250:487–519. doi:10.1007/s10479-015-1858-9

5. Wu R, Li M. Impact of consumer green preferences on pricing decisions in dual-channel supply chains: a complex systems-based dynamic game analysis. *Glob J Flexible Syst Management* (2025) 26:1–20. doi:10.1007/s40171-025-00466-8

6. Song H, Wang Y, Mao X, Wang C. Decision-making in a low-carbon supply chain considering consumers' fairness concerns. *Expert Syst Appl* (2024) 237:121606. doi:10.1016/j.eswa.2023.121606

7. Zhang Z, Sheng N, Zhao D, Cai K, Yang G, Song Q. Are residents more willing to buy and pay for electric vehicles under the "carbon neutrality". *Energy Rep* (2023) 9:510–21. doi:10.1016/j.egyr.2022.11.206

8. Xu Y, Xian B, Ren Y, Wang Y, Lang L, Wang B. Do carbon labels increase Chinese consumers' willingness to pay for carbon-labeled agricultural products? *J Clean Prod* (2024) 434:140299. doi:10.1016/j.jclepro.2023.140299

9. Sarkar B, Bhuniya S. A sustainable flexible manufacturing–remanufacturing model with improved service and green investment under variable demand. *Expert Syst Appl* (2022) 202:117154. doi:10.1016/j.eswa.2022.117154

10. Li F, Xu X, Li Z, Du P, Ye J. Can low-carbon technological innovation truly improve enterprise performance? The case of Chinese manufacturing companies. *J Clean Prod* (2021) 293:125949. doi:10.1016/j.jclepro.2021.125949

11. Li Y, Yao S, Wang J. Signaling strategies in a low-carbon supply chain with platform encroachment. *Transportation Res E: Logistics Transportation Rev* (2023) 179:103319. doi:10.1016/j.tre.2023.103319

12. Guo L, Iyer G. Information acquisition and sharing in a vertical relationship. *Marketing Sci* (2010) 29:483–506. doi:10.1287/mksc.1090.0534

13. Guan X, Chen YJ. The interplay between information acquisition and quality disclosure. *Prod Operations Management* (2017) 26:389–408. doi:10.1111/poms.12651

14. Yao Z, Gendreau M, Li M, Ran L, Wang Z. Service operations of electric vehicle carsharing systems from the perspectives of supply and demand: a literature review. *Transportation Res C: Emerging Tech* (2022) 140:103702. doi:10.1016/j.trc.2022.103702

15. Li G, Liu M, Zheng H. Subsidization or diversification? Mitigating supply disruption with manufacturer information sharing. *Omega* (2022) 112:102670. doi:10.1016/j.omega.2022.102670

16. Xie J. Information sharing in a supply chain with asymmetric competing retailers. *Sustainability* (2022) 14:12848. doi:10.3390/su141912848

17. Kong G, Rajagopalan S, Zhang H. Revenue sharing and information leakage in a supply chain. *Management Sci* (2013) 59:556–72. doi:10.1287/mnsc.1120.1627

18. Yan Y, Zhao R, Lan Y. Asymmetric retailers with different moving sequences: group buying vs. individual purchasing. *Eur J Oper Res* (2017) 261:903–17. doi:10.1016/j.ejor.2017.02.025

19. Benjaafar S, Li Y, Daskin M. Carbon footprint and the management of supply chains: insights from simple models. *IEEE Transactions Automation Science Engineering* (2012) 10:99–116. doi:10.1109/tase.2012.2203304

20. Ji J, Zhang Z, Yang L. Carbon emission reduction decisions in the retail-/dual-channel supply chain with consumers' preference. *J Cleaner Production* (2017) 141:852–67. doi:10.1016/j.jclepro.2016.09.135

21. Liu J, Ke H, Tian G. Impact of emission reduction investments on decisions and profits in a supply chain with two competitive manufacturers. *Comput Ind Eng* (2020) 149:106784. doi:10.1016/j.cie.2020.106784

22. Du S, Wang L, Hu L, Zhu Y. Platform-led green advertising: promote the best or promote by performance. *Transportation Res Part E: Logistics Transportation Rev* (2019) 128:115–31. doi:10.1016/j.tre.2019.05.019

23. Wang S, Liu L, Wen J, Wang G. Product pricing and green decision-making considering consumers' multiple preferences under chain-to-chain competition. *Kybernetes* (2024) 53:152–87. doi:10.1108/k-05-2022-0782

24. Wu R, Li M. The impact of blockchain on carbon reduction in remanufacturing supply chains within the carbon trading market: a chaos and bifurcation analysis. *Nonlinear Dyn* (2025) 113:1–34. doi:10.1007/s11071-025-11183-3

25. Lu J, Sun X. Carbon regulations, production capacity, and low-carbon technology level for new products with incomplete demand information. *J Clean Prod* (2021) 282:124551. doi:10.1016/j.jclepro.2020.124551

26. Gao M, Xia L, Xiao Q, Goh M. Incentive strategies for low-carbon supply chains with information updating of customer preferences. *J Clean Prod* (2023) 410:137162. doi:10.1016/j.jclepro.2023.137162

27. Wang Y, Wang Q, Shi J. Demand forecast information sharing in low-carbon supply chains. *Sustainability* (2024) 16:9056. doi:10.3390/su16209056

28. Cachon GP, Fisher M. Supply chain inventory management and the value of shared information. *Management Science* (2000) 46:1032–48. doi:10.1287/mnsc.46.8.1032.12029

29. Li Z, Gilbert SM, Lai G. Supplier encroachment under asymmetric information. *Management Sci* (2014) 60:449–62. doi:10.1287/mnsc.2013.1780

30. Zhang L-H, Zhang C. Manufacturer encroachment with capital-constrained competitive retailers. *Eur J Oper Res* (2022) 296:1067–83. doi:10.1016/j.ejor.2021.05.027

31. Avinadav T, Shamir N. Truth, trust, and trade-offs: when blockchain in supply chains backfires. *Eur J Oper Res* (2025) 326:467–80. doi:10.1016/j.ejor.2025.05.011

32. Desai PSJMS *Multiple messages to retain retailers: signaling new product demand*, 19 (2000). p. 381–9.

33. Jiang B, Tian L, Xu Y, Zhang F. To share or not to share: demand forecast sharing in a distribution channel. *Marketing Sci* (2016) 35:800–9. doi:10.1287/mksc.2016.0981

34. Cao Y, Wang Q. The informational role of guarantee contracts. *Eur J Oper Res* (2022) 301:191–202. doi:10.1016/j.ejor.2021.10.022

35. Guo L. Upstream exploitation and strategic disclosure. *Marketing Sci* (2020) 39:923–38. doi:10.1287/mksc.2019.1216

36. Wang S, Gurnani H, Subramanian U. The informational role of buyback contracts. *Management Sci* (2021) 67:279–96. doi:10.1287/mnsc.2019.3552

37. Khouja M, Park S, Cai GG. Channel selection and pricing in the presence of retail-captive consumers. *Int J Prod Econ* (2010) 125:84–95. doi:10.1016/j.ijpe.2010.01.005

38. Liu H, Wei Z, Hu D, Yang J, Linghu D. Robust financing decisions of green supply chain under market risk. *Sustainability* (2024) 16:7942. doi:10.3390/su16187942

39. Ha AY, Tian Q, Tong S. Information sharing in competing supply chains with production cost reduction. *Manufacturing Serv Operations Management* (2017) 19:246–62. doi:10.1287/msom.2016.0607

40. Zhang Q, Tang W, Zaccour G, Zhang J. Should a manufacturer give up pricing power in a vertical information-sharing channel? *Eur J Oper Res* (2019) 276:910–28. doi:10.1016/j.ejor.2019.01.054

41. Nordhaus WD. To slow or not to slow: the economics of the greenhouse effect. *The Economic Journal* (1991) 101:920–37. doi:10.2307/2233864

42. Bai Q, Xu J, Chauhan SS. Effects of sustainability investment and risk aversion on a two-stage supply chain coordination under a carbon tax policy. *Comput Ind Eng* (2020) 142:106324. doi:10.1016/j.cie.2020.106324

43. Cao E, Chen G. Information sharing motivated by production cost reduction in a supply chain with downstream competition. *Naval Res Logistics* (2021) 68:898–907. doi:10.1002/nav.21977

44. Wu R, Li M. Optimization of shipping freight forwarding services considering consumer rebates under the impact of carbon tax policy. *Ocean Coastal Management* (2024) 258:107361. doi:10.1016/j.ocecoaman.2024.107361

45. Yang D, Xiao T. Pricing and green level decisions of a green supply chain with governmental interventions under fuzzy uncertainties. *J Clean Prod* (2017) 149:1174–87. doi:10.1016/j.jclepro.2017.02.138

46. Dai R, Zhang J, Tang W. Cartelization or cost-sharing? Comparison of cooperation modes in a green supply chain. *J Clean Prod* (2017) 156:159–73. doi:10.1016/j.jclepro.2017.04.011

47. Wu R, Li M, Liu F, Zeng H, Cong X. Adjustment strategies and chaos in duopoly supply chains: the impacts of carbon trading markets and emission reduction policies. *Int Rev Econ Finance* (2024) 95:103482. doi:10.1016/j.iref.2024.103482