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Consumer Orientation and Market-Driven Strategies for Promoting Low-Carbon Innovation in Supply Chains: Pathways to Sustainable Development

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Abstract: As environmental challenges become increasingly pressing, companies are integrating low-carbon innovations into supply chain management to achieve economic performance while promoting environmental sustainability and social responsibility. This study explores how low-carbon innovation in supply chains can be driven by consumer orientation and market-driven strategies, contributing to sustainable development. Using Stackelberg game theory, the study develops centralized and decentralized decision-making models and solves them through differential game methods. Numerical simulations are employed to analyze the impact of consumer preferences for low-carbon products and market strategies on supply chain decisions and overall profitability. The results show that consumer demand for low-carbon products plays a crucial role in driving low-carbon innovation within supply chains. Market strategies, particularly their sensitivity to consumer preferences, significantly influence decision-making processes. Further analysis reveals that the centralized decision-making model offers greater advantages in resource optimization and responsiveness to market shifts, while the decentralized model allows independent decision-making by supply chain participants, balancing competition and co-operation. This enables firms to achieve both economic benefits and reduce their environmental footprint, thereby contributing to sustainable development. This research highlights the importance of aligning consumer demand with market strategies to foster low-carbon innovation. The findings provide valuable theoretical insights and practical strategies to help supply chain companies enhance their competitiveness and contribute to the sustainable development of global supply chains.

Keywords: low-carbon innovation; consumer preferences; supply chain; realization mechanisms; Stackelberg game; sustainable development

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1. Introduction

As global climate change becomes increasingly pressing, a low-carbon economy has emerged as a crucial strategic goal for economic development worldwide. According to data from the International Energy Agency (IEA), global carbon dioxide emissions reached a record high of 4.09 billion tons in 2022. In response, more than 130 countries and regions have pledged to achieve carbon neutrality by 2050. As the world's largest carbon emitter, China has set its own targets of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. Governments around the world continue to introduce policies and regulations aimed at accelerating businesses' transition toward low-carbon and sustainable practices. In this context, low-carbon innovation in supply chains has become an urgent necessity.

Manufacturers, retailers, and consumers play key roles in advancing low-carbon economic development within supply chains [1]. Manufacturers are expected to integrate low-carbon technologies into their production processes to reduce carbon emissions while simultaneously enhancing the environmental performance of their products. Retailers, on the other hand, must engage in market development and promotional efforts to raise consumer awareness and acceptance of low-carbon products. As consumers become increasingly environmentally conscious, their demand for low-carbon products grows. However, they also expect that product cost-performance ratios and user experience will remain unaffected [2]. Businesses are, therefore, faced with the challenge of meeting consumer needs while undergoing low-carbon transitions, placing greater demands on all levels of the supply chain. Existing studies show that manufacturers face significant technical and cost-related challenges when adopting low-carbon technologies. Retailers also need to better understand consumer behavior and employ more sophisticated marketing strategies to effectively promote low-carbon products [1,3,4]. While consumers' environmental awareness is on the rise, their willingness to purchase low-carbon products is still influenced by factors such as price and product performance [5]. Thus, the successful implementation of low-carbon innovation within supply chains is of critical importance to all stakeholders.

However, several challenges hinder the practical implementation of low-carbon innovations in supply chains. First, the development and application of low-carbon technologies and equipment require substantial investment, resulting in high initial costs for businesses [4]. Second, many low-carbon technologies are still in the early stages of development, with breakthroughs in core areas yet to be achieved [6]. Additionally, disparities in technological application and research capabilities among supply chain members have led to uneven progress, making coordinated innovation efforts difficulty [7]. Furthermore, regulatory uncertainty complicates long-term strategic planning for businesses. Consumer awareness and acceptance of low-carbon products remain limited, and the full potential of market demand has yet to be realized [8]. Finally, the coordination of various supply chain elements—including manufacturers, retailers, and logistics providers—is complex, with insufficient information sharing restricting overall supply chain optimization and collaborative innovation [9]. As such, overcoming these challenges and successfully achieving low-carbon innovation within supply chains is an urgent issue that needs to be addressed.

2. Literature Review

2.1. Stackelberg Game Model

The Stackelberg game, proposed by German economist Heinrich von Stackelberg in 1934, is a dynamic game theory model that studies the strategic interaction between leaders and followers in market competition. Unlike other game models such as the Cournot competition model, which assumes firms choose their strategies simultaneously, the Stackelberg game assumes that one party, the leader, moves first, while the other party, the follower, reacts to the leader's action. This sequence of moves leads to a first-mover advantage for the leader, which can influence the follower's decisions and shape the overall market outcome [10].

The Stackelberg game model is widely used in oligopolistic markets to model interdependent decision-making among firms. For instance, in a duopoly where Firm A is the leader and Firm B is the follower. Firm A chooses its output (Q_A) first, and Firm B observes this before selecting its own output (Q_B). The market price p is determined by the total output, $p = p(Q)$, where $Q = Q_A + Q_B$. The profit functions of Firm A and Firm B are represented as $\pi_A = P(Q)q_A - C_A q_A$ and $\pi_B = P(Q)q_B - C_B q_B$, respectively. When

Firm A selects its output (q_A), it considers the response function of Firm B. The response function of Firm B indicates the optimal output for Firm B given the output (q_B) of Firm A. Firm B's best response function $q_B = f(q_A)$ can be derived by solving Firm B's profit maximization problem. Firm A, in turn, incorporates Firm B's response function into its own profit function to solve for its optimal output (q_A) [9,11].

Stackelberg game theory is a non-co-operative game model widely used in economics and management, especially in scenarios involving decision dynamics between leaders and followers. In this model, participants typically make decisions sequentially, with the leader choosing their strategy first, and the follower selecting the optimal response based on the leader's decision. The model has two key assumptions. Assumption 1: Clear Roles of Leader and Follower: In a Stackelberg game, the roles of the leader and follower are fixed. The leader has a first-mover advantage and can influence or determine the decisions of the follower. Assumption 2: Information Symmetry: The leader usually has complete information, while the follower makes decisions based on this information. In some cases, the follower may know the decision rules and intentions of the leader but is unaware of the leader's actual decision [12].

While the Stackelberg game assumes the leader possesses complete information and makes decisions accordingly, information symmetry does not always hold true in low-carbon supply chains. Manufacturers may have incomplete knowledge about market demand, consumer preferences, or policy changes. Consequently, some researchers suggest that in situations with information asymmetry, Bayesian games can describe the beliefs and expectations of each party through probability distributions [13].

Although, in practice, manufacturers in low-carbon supply chains may not have complete information about market demand and consumer preferences, the assumptions of the Stackelberg game remain applicable. In such situations, even if the manufacturer faces incomplete information, their decisions still significantly influence the behavior of the retailer. The core issue in low-carbon supply chains is how the manufacturer's decisions and the retailer's responses drive the adoption of low-carbon technologies and the promotion of the market. The Stackelberg game model, with its clear sequential decision-making structure, effectively captures this process [14].

The assumptions in the Stackelberg game typically emphasize the behavior of supply-side players (manufacturers and retailers), but in low-carbon supply chains, consumer demand plays a critical role. Consumer preferences for low-carbon products (such as price sensitivity and carbon reduction sensitivity) directly affect supply and demand decisions in the supply chain. By incorporating consumer preferences into the Stackelberg game model, particularly within the framework of consumer orientation and market strategies, the model can more accurately capture the interactions between all parties in the supply chain [15].

Therefore, in low-carbon supply chains, this framework helps explain how manufacturers and retailers co-operate and compete when information is lacking. Compared to other game models, such as Bayesian games, the Stackelberg game provides a more intuitive analytical framework, making it well-suited for quantitative analysis of the promotion of low-carbon innovation in this research.

2.2. The Impact of Consumer Orientation on Low-Carbon Innovation in Supply Chains

Consumer orientation refers to a business strategy focused on meeting consumer demands and preferences across all stages of product and service design, production, and sales [16]. As consumer awareness of environmental issues increases, low-carbon consumption has gradually become a new consumption trend. Against this backdrop, the influence of consumer orientation on low-carbon innovation within supply chains has attracted widespread attention from scholars both domestically and internationally.

First, the rise in environmental consciousness among consumers is one of the main driving forces behind low-carbon innovation in supply chains. Consumer preferences for low-carbon products directly affect companies' production and market strategies. Research indicates that consumer preferences for low-carbon products can significantly enhance corporate low-carbon innovation [17]. These consumers tend to choose products that emit less carbon during production and use, encouraging companies to adopt low-carbon technologies across all segments of the supply chain. In a decentralized strategy, manufacturers and retailers co-operate through various models to meet consumer demand for low-carbon products and improve the environmental performance of the supply chain [18].

Second, retailers play a crucial role within supply chains by directly interacting with end consumers, and their ability to promote low-carbon products has a direct impact on the effectiveness of low-carbon innovation. Studies show that retailer promotional strategies, whether within a decentralized or centralized model, can significantly improve consumer awareness and acceptance of low-carbon products [19]. In promoting low-carbon products, retailers can use in-store marketing and environmentally themed promotional activities to increase consumer purchasing intention, which in turn motivates manufacturers to adopt more low-carbon technologies in product design and production. Through decentralized strategies, retailers can employ various marketing methods to flexibly respond to different market demands, while in centralized strategies, retailers can promote low-carbon products through unified branding, thereby enhancing their market recognition [9].

Moreover, consumer attention to a company's low-carbon image drives continuous efforts by businesses to innovate within supply chains. Research suggests that the degree of importance consumers attach to a company's low-carbon image significantly influences the company's investment in low-carbon innovation [20]. By actively cultivating a low-carbon image, businesses can enhance brand reputation and consumer loyalty, ultimately gaining a larger market share. For instance, companies may engage in environmental public welfare activities, publish corporate social responsibility reports, and showcase their efforts and achievements in low-carbon innovation.

2.3. The Impact of Market Strategies on Low-Carbon Innovation in Supply Chains

Market strategy selection has a significant impact on the pathways and outcomes of low-carbon innovation in supply chains, especially for manufacturers and retailers. Decentralized and centralized strategies each have distinct advantages in fostering low-carbon innovation.

Decentralized strategies emphasize multi-party co-operation and flexibility in responding to market demand. Game theory models have been used to analyze the co-operative mechanisms between manufacturers and retailers in market strategy, proposing multi-faceted co-operation to achieve low-carbon innovation within supply chains. In decentralized strategies, manufacturers and retailers collaborate through various models to drive low-carbon innovation [21]. For example, manufacturers can work with multiple raw material suppliers, utilizing renewable materials and green production technologies to reduce carbon emissions in production. Retailers, in turn, can partner with multiple logistics service providers to optimize distribution routes and adopt low-carbon transportation methods, thereby reducing the carbon footprint of logistics. Scholars using differential game models have demonstrated that co-operative strategies effectively promote low-carbon innovation and improve the overall environmental performance of the supply chain [22]. Decentralized strategies also allow manufacturers and retailers to adjust their low-carbon measures in response to shifting market demands [23]. By employing decentralized strategies, companies can diversify risks in supply chain management, avoiding uncertainties associated with reliance on a single partner or market strategy.

Centralized strategies, in contrast, emphasize unified planning and coordinated management in promoting low-carbon innovation. In centralized models, manufacturers and retailers can implement low-carbon innovation measures more effectively through centralized decision-making and marketing strategies. Centralized strategies allow for unified planning and management of all aspects of the supply chain, ensuring that low-carbon measures are consistently applied [24]. Researchers also suggest that collaborative emission reduction efforts between upstream and downstream companies can significantly enhance efficiency through economies of scale [25]. Under a centralized approach, manufacturers and retailers can engage in unified brand promotion and market campaigns to improve the market recognition and reputation of low-carbon products. Some scholars argue that while there are differences in the level of effort between retailers in Nash and Stackelberg co-operative strategies, overall co-operation leads to optimal supply chain configurations, enhancing low-carbon innovation efficiency [10]. Centralized strategies enable cost reduction through bulk purchasing and large-scale production. For instance, manufacturers can purchase environmentally friendly materials and equipment in bulk, reducing unit costs and improving the market competitiveness of low-carbon products. Similarly, retailers can reduce logistics costs and carbon emissions by consolidating procurement and distribution of low-carbon products. Retailers' promotional strategies, whether implemented in decentralized or centralized models, have been shown to significantly increase consumer awareness and acceptance of low-carbon products, thereby expanding market share and driving low-carbon innovation [18].

3. Research Methodology

3.1. Research Approach

This study employs a combination of the Mathematical Modeling Method and simulation methods to analyze the optimal decision-making behaviors of manufacturers and retailers in the supply chain under different decision-making models. Specifically, the Stackelberg game theory model is constructed to examine how these decisions affect the overall profit of the supply chain and consumer surplus. The study ensures the concavity of the profit function by constructing the Hessian matrix and verifying its negative definiteness, confirming that the economic profit function is concave under certain conditions. Subsequently, backward induction is applied to solve the low-carbon innovation problems in both centralized and decentralized decision-making models.

3.1.1. Mathematical Modeling Method

Mathematical modeling is one of the core methods used in this study. By introducing Stackelberg game theory, this research constructs a low-carbon innovation effect model for the supply chain, focusing on analyzing the strategy choices of manufacturers and retailers under both centralized and decentralized decision-making scenarios and their mutual impacts. Through this mathematical modeling approach, we can quantitatively analyze the interactions between the behaviors of different parties in the supply chain and their influence on the overall supply chain efficiency.

Specifically, the centralized decision-making model assumes that all participants in the supply chain co-operate to optimize overall benefits, whereas the decentralized decision-making model assumes that each supply chain member makes decisions independently, aiming to maximize their own profit. Based on this framework, the study employs differential game theory to solve the models and uses backward induction to analyze the decision-making processes of manufacturers and retailers, ultimately deriving specific expressions for the equilibrium retail price, carbon reduction level, and low-carbon marketing efforts [1,3].

The mathematical modeling method not only helps reveal the decision-making behaviors under different strategies but also provides a theoretical foundation for subsequent empirical analysis. Through the construction and solution of the models, this study deepens our understanding of the key drivers in the low-carbon innovation process, highlighting the roles of market strategies and consumer orientation in promoting low-carbon innovation, ultimately offering valuable theoretical guidance for supply chain management [26].

3.1.2. Simulation Methodology

To provide a more intuitive illustration of how supply chain decision-making affects economic outcomes, the study utilizes numerical simulation methods to model and validate the theoretical framework. Tools such as Matlab are used to simulate the effects of consumer preferences for low-carbon products, pricing strategies, and low-carbon marketing efforts on the decisions of supply chain entities and the overall system profit [27].

The use of simulation methods allows researchers to test how the model performs under various conditions and assumptions, helping to verify the reliability and applicability of the theoretical findings. This study simulates different consumer demand elasticities for low-carbon products and investigates how supply chain members adjust pricing, production, and marketing strategies under different market conditions to optimize the low-carbon innovation outcomes. The simulation results provide practical insights for decision-makers, particularly in balancing economic and environmental benefits, offering valuable guidance for achieving sustainable development.

3.2. Research Variables

This study uses Stackelberg game theory to analyze the impact of consumer orientation and market strategies on the optimal decision-making behaviors of manufacturers and retailers in the supply chain under different decision-making models. The goal of the study is to explore how these behaviors affect the overall profit of the supply chain and consumer surplus, thereby revealing the underlying mechanisms for achieving low-carbon innovation in the supply chain. This study references the research methods of Su and Tang, using the price sensitivity coefficient (b) and carbon reduction sensitivity coefficient (α) to analyze consumer behavior [1,14]. The low-carbon promotion sensitivity coefficient (β) is used to study the impact of marketing strategies on consumer awareness and acceptance of low-carbon products [15].

Meanwhile, the market strategy variables are based on the research of Das and Wang, including the manufacturer's decision variable (e) and the retailer's decision variable (g), which reflect strategic choices related to reducing carbon emissions and promoting low-carbon products. These decision variables are based on Stackelberg game theory, where the manufacturer and retailer make sequential decisions. The manufacturer's decision to invest in low-carbon technologies and the retailer's decision to enhance promotional efforts are influenced by research on supply chain operations and strategies for achieving low-carbon innovation [15,28].

The selection of these variables reflects the dynamic interactions and strategic behaviors within the supply chain that contribute to low-carbon innovation. By incorporating these variables into the Stackelberg game framework, this study focuses on the impact of consumer preferences and market strategies on the decisions of manufacturers and retailers, and ultimately reveals their role in driving the overall performance of the supply chain in promoting sustainability and low-carbon innovation. (see Table 1).

Table 1. Research variables.

Item	Category	Frequency
Consumer Orientation	Price Sensitivity Coefficient (b)	Reflects the sensitivity of consumers to price changes. The higher the price, the lower the demand. This coefficient measures the price-oriented characteristics of consumers.
	Carbon Reduction Sensitivity Coefficient (α)	Represents consumers' sensitivity to the carbon reduction level of a product. The higher the carbon reduction, the greater the consumer demand. This coefficient reflects consumers' environmental concerns regarding low-carbon products.
	Low-Carbon Promotion Sensitivity Coefficient (β)	Indicates the sensitivity of consumers to low-carbon marketing. The greater the retailer's low-carbon promotional efforts, the higher the consumer demand. This coefficient reflects the degree to which consumers are influenced by market strategies.
Market Strategy	Manufacturer's Decision Variable (e)	Represents the manufacturer's decision to reduce carbon emissions through increased investment in low-carbon technologies, which improves market demand and product competitiveness.
	Retailer's Decision Variable (g)	Represents the retailer's decision to increase low-carbon promotional efforts, enhancing consumer awareness and acceptance of low-carbon products, thereby boosting market demand.
Police	Green Subsidy (S_g)	Financial incentives provided by the government to reduce the cost of carbon reduction (C_m) and marketing effort costs (C_r).
	Subsidy rate (σ)	Represents different subsidy rates

3.3. Model Construction

To further explore the impact of manufacturers' low-carbon production and retailers' low-carbon marketing efforts on the decision-making and related profits of supply chain firms at various nodes, this study incorporates both consumer orientation and market strategies when constructing the low-carbon innovation decision model. In this model, the study assumes that the supply chain consists of two main entities: manufacturers and retailers. The manufacturer, as the leader in the supply chain, is responsible for product production and investments in low-carbon technologies, while the retailer, as the follower, is responsible for product sales and low-carbon promotional efforts. Parameter descriptions are provided in Table 1. The specific model construction is as follows:

3.3.1. Market Demand Function

Assume that the product demand in the market is influenced by multiple factors and can be expressed by the following equation (Formula (1)):

$$Q = Q_0 - bp + \alpha e + \beta g \quad (1)$$

3.3.2. Cost Function

Considering the impact of external environmental changes on costs, this study introduces a dynamic cost model:

$$C_0 = C_m + C_r + \theta_m * \Delta R + \vartheta_m * \Delta P + k_m * \Delta T$$

$\theta_m, \vartheta_m, k_m$: Changes in raw material availability, regulatory conditions, and technology.
$\Delta R\ \Delta P\ \Delta T$: Sensitivity coefficients for the manufacturer's costs.

3.3.3. Supply Chain Profit Function

Manufacturer's Decision Variable: The manufacturer reduces carbon emissions by increasing investment in low-carbon technologies, thereby improving the market demand

and competitiveness of the product. The manufacturer's profit function can be expressed as (Formula (2)):

$$\prod_m = (\omega - C_0)Q - k_m e^2 \quad (2)$$

3.3.4. Retailer's Decision Variable

The retailer increases consumer awareness and acceptance of low-carbon products by intensifying low-carbon promotional efforts, thereby enhancing market demand. The retailer's profit function can be expressed as (Formula (3)):

$$\prod_r = (p - \omega)Q - k_r g^2 \quad (3)$$

3.3.5. Supply Chain Economic Profit Function

Assume that the total profit of the supply chain is the sum of the profits of the manufacturer and the retailer (Formula (4)):

$$\prod_{sc} = \prod_m + \prod_r \quad (4)$$

4. Construction of the Stackelberg Game Model

4.1. Model Calculation and Validation

Low-Carbon Innovation Models in Supply Chains Under Different Decision-Making Models

(1) Low-Carbon Innovation Model in Supply Chains under Centralized Decision-Making

In the centralized decision-making model, the manufacturer and the retailer make decisions as a unified entity with the goal of maximizing the overall profit of the entire supply chain. The manufacturer engages in low-carbon production, while the retailer undertakes low-carbon marketing efforts. Both parties collaborate to jointly determine the product price p, the product's carbon reduction level e, and the level of low-carbon marketing efforts g. The economic profit function of the supply chain can thus be expressed as a three-variable function of p, e, g. Therefore, this study proposes that when $b > 0$, $2bk_m - \alpha^2 > 0$, $k_r\alpha^2 + k_m\beta^2 - 2bk_m k_r < 0$, the economic profit function of the supply chain is a concave function with respect to p, e, g.

To verify the concavity of the economic profit function, this study use the Hessian matrix, which is a square matrix of second-order partial derivatives. A function is concave if its Hessian matrix is negative definite. Below are the steps to construct the Hessian matrix and calculate the first-order derivatives of the economic profit function with respect to p, e, g. Assume the economic profit function of the supply chain is represented as $\prod_{sc}(p, e, g)$.

Construct the Hessian matrix to verify its negative quality.

First, the first derivative of each variable is calculated (Formulas (5) and (6)).

$$\frac{\partial \prod_{sc}}{\partial p} = Q_0 - 2bp + \alpha e + \beta g \quad (5)$$

$$\frac{\partial \prod_{sc}}{\partial e} = \alpha p - 2k_m e \quad (6)$$

$$\frac{\partial \prod_{sc}}{\partial e} = \beta p - 2k_\gamma g \quad (7)$$

The Hessian matrix H is constructed according to the second derivative (Formula (8)).

$$H = \begin{bmatrix} \frac{\partial^2 \prod_{sc}}{\partial p^2} & \frac{\partial^2 \prod_{sc}}{\partial p \partial e} & \frac{\partial^2 \prod_{sc}}{\partial p \partial g} \\ \frac{\partial^2 \prod_{sc}}{\partial e \partial p} & \frac{\partial^2 \prod_{sc}}{\partial e^2} & \frac{\partial^2 \prod_{sc}}{\partial e \partial g} \\ \frac{\partial^2 \prod_{sc}}{\partial g \partial p} & \frac{\partial^2 \prod_{sc}}{\partial g \partial e} & \frac{\partial^2 \prod_{sc}}{\partial g^2} \end{bmatrix} = \begin{bmatrix} -2b & \alpha & \beta \\ \alpha & -2k_m & 0 \\ \beta & 0 & -2k_r \end{bmatrix} \tag{8}$$
$$= -2b * (-2k_r) - \alpha * \alpha * (-2k_r) - \beta * \beta * (-2k_m)$$
$$= k_r \alpha^2 + k_m \beta^2 - 2bk_m k_r < 0$$

Therefore, when $b > 0$, $2bk_m - \alpha^2 > 0$, $k_r\alpha^2 + k_m\beta^2 - 2bk_mk_r < 0$, the supply chain economic profit function is a concave function with respect to and p, e, g.

Derive the supply chain economic profit model under the centralized decision model.

According to the calculation, the balanced carbon emission reduction (e^*_{cc}), the balanced low-carbon publicity effort level (g^*_{cc}), and the balanced retail price are respectively obtained (p^*_{cc}) (Formulas (9)–(11)).

$$P^*_{cc} = \frac{Q_0}{2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}} \tag{9}$$

$$e^*_{cc} = \frac{\alpha Q_0}{2k_m}(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}) \tag{10}$$

$$g^*_{cc} = \frac{\beta Q_0}{2k_r(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r})} \tag{11}$$

The above equilibrium solution indicates that, under the centralized decision-making mode, supply chain enterprises strive to maximize profits through optimal pricing, carbon emission reduction, and low-carbon publicity. Therefore, the supply chain economic profit function is obtained (Formulas (12)–(14)).

$$\begin{aligned}\prod_{sc} = &\left(\frac{Q_0}{2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}} - \omega\right)\left(Q_0 - b\frac{Q_0}{2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}}\right) + \frac{\alpha Q_0}{2k_m}\left(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}\right) \\ &+\beta \frac{\beta Q_0}{2k_r\left(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}\right)} - k_m\left(\frac{\alpha Q_0}{2k_r\left(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}\right)}\right) - k_r\left(\frac{\beta Q_0}{2k_r\left(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}\right)}\right)\end{aligned} \tag{12}$$

According to the above equilibrium solution, the consumer surplus is obtained:

$$Q_{cc} = Q_0\left(1 - \frac{b}{2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}} + \frac{\alpha^2}{2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}} + \frac{\beta^2}{2k_r\left(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}\right)}\right) \tag{13}$$

$$CS_{cc} = \frac{1}{2}Q_{cc}(v - \frac{Q_0}{2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}}) \tag{14}$$

Therefore, in the centralized decision model, the consumer surplus CS reflects the total welfare that the consumer gets from the purchase of the product in the equilibrium state.

(2) Construction of the Low-Carbon Innovation Performance Model under Decentralized Decision-Making

In the decentralized decision-making model, the manufacturer and retailer within the supply chain make decisions independently, each aiming to maximize their own profit. The manufacturer, acting as the leader of the supply chain, first makes decisions regarding low-carbon production and pricing. The retailer, acting as the follower, then makes decisions on low-carbon marketing and sales pricing based on the manufacturer's decisions. In the decentralized decision-making model, the decisions between the manufacturer and retailer can be analyzed using a Stackelberg game model. This study applies the backward induction method to solve the model, where the manufacturer, as the leader, makes decisions first, followed by the retailer, who makes decisions afterward. Therefore, this study proposes that when $b > 0$, $2bk_m - \alpha^2 > 0$, $k_r\alpha^2 + k_m\beta^2 - 2bk_mk_r < 0$, the manufacturer's economic profit function ($\prod_m$) is a concave function with respect to the wholesale price (ω), product carbon reduction level (e), and the level of low-carbon marketing efforts (g).

① Retailer decision

Based on the outcome of the manufacturer's decision, the retailer determines its optimal retail price (p) and low-carbon promotional effort level (g) to maximize its profits. The profit function of the retailer is Formula (15).

$$\prod_r = (p - \omega)(Q_0 - bp + \alpha e + \beta g) - k_r g^2 \tag{15}$$

Based on the manufacturer's wholesale price and carbon reduction level e, the retailer determines its optimal retail price p and low-carbon promotional effort level (g). First, the first derivative of retailer's profit function is solved and set to zero to obtain retailer's response function (Formulas (16)–(18)).

$$\frac{\partial \prod_r}{\partial p} = Q_{0-}2bp + \alpha e + \beta g - \omega b = 0 \tag{16}$$

$$\frac{\partial \prod_r}{\partial g} = \beta(Q_{0-}2bp + \alpha e + \beta g) - 2k_r g = 0 \tag{17}$$

Therefore, the equilibrium price of the retailer is:

$$P_r^* = \frac{Q_0 + \alpha e + \frac{\beta(Q_0 + \alpha e - \omega b)}{4k_r - \beta^2} + \omega b}{2b} \tag{18}$$

② Manufacturer's decision

Manufacturers determine their optimal wholesale price and carbon reduction level e to maximize their profits. The profit function of the manufacturer is Formula (19).

$$\prod_m = (\omega - c_m)(Q_0 - bp + \alpha e + \beta g) - k_m e^2 \tag{19}$$

Substitute the retailer's equilibrium solution into the manufacturer's profit function to get the manufacturer's equilibrium price (Formula (20)).

$$p_{cd}^* = \frac{Q_0 + \alpha e + \beta g + \omega b}{2b} \tag{20}$$

Therefore, the equilibrium retail price (p), carbon emission reduction (e), and low-carbon publicity effort levels under the decentralization strategy are as follows (Formulas (21)–(26)):

$$P_{cd}^* = \frac{Q_0 + \alpha e_{cd} + \beta g_{cd} + \omega b}{2b} \tag{21}$$

$$e_{cd}^* = \frac{\alpha Q_0}{2k_m\left(2b - \frac{\alpha^2}{2k_m} - \frac{\beta^2}{2k_r}\right)} \tag{22}$$

$$g_{cd}^* = \frac{\beta(Q_0 + \alpha e_{cd} - \omega b)}{4k_r - \beta^2} \tag{23}$$

Supply chain profit is:

$$\prod_{cd} = \frac{-k_m k_r Q_0^2 \left(k_r \alpha^2 + 3k_m \beta^2 - 6bk_m k_r\right)}{2\left(k_r \alpha^2 + 4k_m \beta^2 - 6bk_m k_r\right)} \tag{24}$$

The consumer surplus is:

$$Q_{cd} = Q_0 - b\left(\frac{Q_0 + \alpha e_{cd} + \beta g_{cd} + \omega b}{2b}\right) + \alpha e_{cd} + \beta g_{cd} \tag{25}$$

$$CS_{cd} = \frac{1}{2} * Q_{cd}\left(v - \frac{Q_0 + \alpha e_{cd} + \beta g_{cd} + \omega b}{2b}\right) \tag{26}$$

Therefore, in the decentralized decision model, the consumer surplus CS reflects the total welfare that the consumer gets from the purchase of the product in the equilibrium state.

(3) Interactive relationship between consumer orientation and marketing strategy

In a low-carbon innovation supply chain, the interaction between consumer orientation and market strategy may significantly affect the economic and environmental performance of the supply chain. In particular, consumer sensitivity to carbon reduction (α) and low-carbon marketing (β) may not be independent, and they may interact to jointly determine the market demand for products and supply chain profits. Considering the interaction of consumer sensitivity to carbon abatement (α) and low-carbon marketing (β), the profit function of the supply chain can be expressed as (Formula (27)).

$$\prod_{sc}(p, e, g) = Q_0(p - \omega)(1 - bp + \alpha e + \beta g + \gamma \alpha \beta) \tag{27}$$

where, γ is the coefficient of the interaction effect, indicating the influence of the sensitivity interaction of consumer orientation (α and β) on market demand. If consumers are highly sensitive to low-carbon marketing and carbon reduction, interaction effects ($\gamma\alpha\beta$) can have a significant impact on demand, thereby changing supply chain pricing strategies, low-carbon production, and marketing decisions.

(4) Green subsidies and game equilibrium analysis

To incorporate green subsidies into the supply chain model and analyze their impact on game equilibrium, we can construct a Stackelberg game framework where green subsidies directly influence the decisions of manufacturers (leaders) and retailers (followers) (Formulas (28)–(36)).

Green subsidy:

$$S_g = \sigma_m * e^2 + \sigma_r * g^2 \tag{28}$$

Manufacturer profit function:

$$\prod_m = (\omega - C_m) * Q - k_m * e^2 + \sigma_m * e^2 \tag{29}$$

Retailer profit function:

$$\prod_r = (p - \omega) * Q - k_r * g^2 + \sigma_r * g^2 \tag{30}$$

Game equilibrium:

Retailer Optimization (Followers):

$$\frac{\partial \prod_r}{\partial p} = (p - \omega)\frac{\partial Q}{\partial g} - 2k_r g + 2\sigma_r g = 0 \tag{31}$$

The optimal response function of retailer is obtained:

$$p^* = \frac{Q_0 + \alpha e + \beta g + \omega b}{2b} \tag{32}$$

$$g^* = \frac{(p - \omega)\beta}{2b(k_r - \sigma_r)} \tag{33}$$

Manufacturer Optimization (Leader):

$$\frac{\partial \prod_r}{\partial p} = (\omega - C_m)\frac{\partial Q}{\partial g} - 2k_m e + 2\sigma_m e = 0 \tag{34}$$

The retailer's optimal response function is:

$$\omega^* = C_m + \frac{Q_0 - bp^* + \alpha e + \beta g^*}{b + \frac{\beta^2}{2(k_r - \sigma_r)}} \tag{35}$$

$$e^* = \frac{(\omega - C_m)\left(\alpha - \frac{\alpha}{2} + \frac{\beta^2 \alpha}{4b(k_r - \sigma_r)}\right)}{2(k_m - \sigma_m)} \tag{36}$$

4.2. Numerical Simulation

The results of the model were analyzed to a certain extent by means of derivation operations. In order to more intuitively show the impact of decision-making behavior of the supply chain on its returns and the returns of the entire supply chain, this study conducted a numerical sensitivity analysis and simulated demonstration with the help of Matlab 2018a. The influence of the correlation coefficient on decision making and the system-related profits of supply chain nodal enterprises is analyzed. The basic parameter values of the simulation example are shown in Table 2.

Table 2. Basic parameter values.

Parameter	Explain	Value
Q_0	Baseline market demand (market demand when prices, low carbon levels and marketing efforts are all zero)	1000
b	Price sensitivity coefficient reflects the sensitivity of market demand to product price	2
α	Carbon emission reduction sensitivity coefficient represents the sensitivity of consumers to the carbon emission reduction of products	1
β	Low-carbon publicity sensitivity coefficient, indicating the sensitivity of consumers to low-carbon publicity	1
k_m	Low-carbon technology input cost coefficient	0.5
k_r	Low-carbon publicity input cost coefficient	0.5
C_m	Manufacturing cost per unit of product	50

4.2.1. Sensitivity Analysis of the Impact of Consumer Low-Carbon Orientation on Supply Chain Decision-Making

In order to analyze the influence of consumers' low-carbon orientation on supply chain decision-making, this topic changes the value range when other parameters are fixed, and observes its impact on manufacturers and retailers' decision-making as well as the overall benefits of the supply chain.

The set value ranges from 0.2 to 1.8, and changes with 0.2 as the step. The simulation of supply chain decision-making behavior and income under different values is carried out by the Matlab2018 tool (see Tables 3 and 4).

Table 3. Sensitivity analysis of supply chain under centralized decision making.

α	e_{cc}^*	g_{cc}^*	p_{cc}^*	Q_{cc}	Π_{cc}
0.2	0.49	3.25	12.2	24.4	366.05
0.4	0.99	3.29	12.32	24.64	369.66
0.6	1.5	3.34	12.53	25.06	375.84
0.8	2.05	3.42	12.83	25.66	384.83
1	2.65	3.53	13.24	26.47	397.06
1.2	3.3	3.67	13.77	27.54	413.1
1.4	4.05	3.86	14.46	28.92	433.8
1.6	4.91	4.09	15.35	30.7	460.44
1.8	5.94	4.4	16.5	32.99	494.87

Table 4. Sensitivity analysis of supply chain under decentralized decision-making.

α	e_{cd}^*	g_{cd}^*	p_{cd}^*	Q_{cd}	Π_{cd}	Π_m	Π_r
0.2	0.2	1.35	22.61	10.13	151.89	126.26	88.86
0.4	0.41	1.36	22.71	10.17	152.51	126.66	89.59
0.6	0.61	1.36	22.86	10.24	153.55	127.35	90.82
0.8	0.83	1.38	23.08	10.34	155.03	128.33	92.58
1	1.05	1.4	23.37	10.47	156.98	129.6	94.92
1.2	1.28	1.42	23.74	10.63	159.42	131.18	97.9
1.4	1.52	1.44	24.18	10.83	162.42	133.11	101.61
1.6	1.77	1.48	24.72	11.07	166.01	135.39	106.16
1.8	2.04	1.51	25.35	11.35	170.28	138.06	111.69

(1) Trends of carbon emission reduction level (e) and low-carbon publicity effort level (g) with consumers' low-carbon sensitivity (α) under centralized decision-making mode (Figure 1).

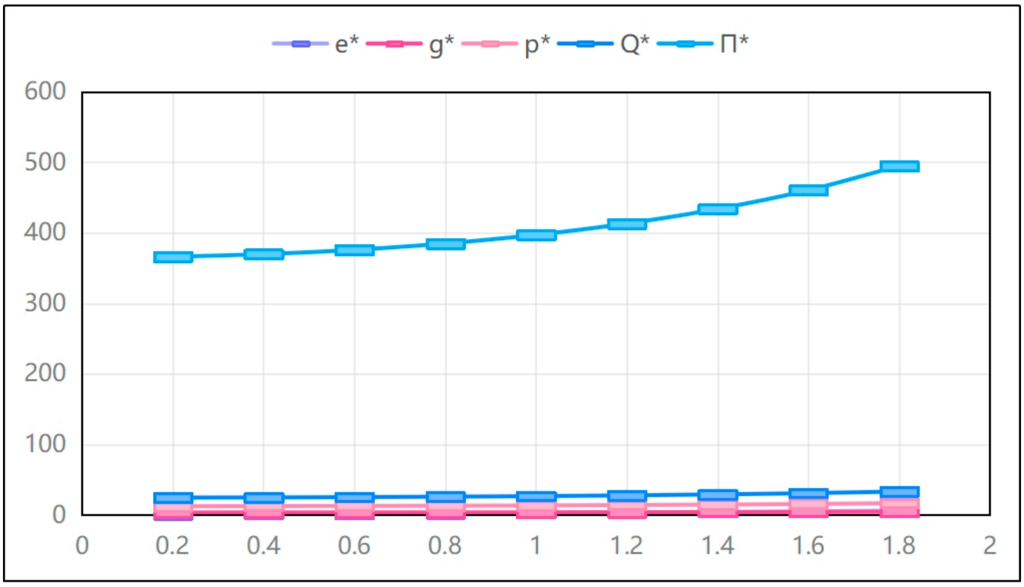

Figure 1. Variation trend of variables under centralized decision-making with consumers' low-carbon sensitivity (α).

The level of carbon emission reduction increases significantly nonlinearly with the increase in α: In the centralized decision-making mode, the investment of manufacturers in carbon emission reduction increases significantly with the increase. As the overall goal of the supply chain is to maximize profits, manufacturers and retailers, through coordinated decision-making, choose to significantly increase the level of carbon reduction under the higher low-carbon preferences of consumers to better meet the market demand.

The level of low-carbon publicity efforts increases nonlinearly with the increase in α: Under the centralized decision-making mode, retailers also significantly increase the intensity of low-carbon publicity with the increase. This non-linear upward trend indicates that, under the centralized decision-making model, coordination among supply chain members can more effectively enhance the effect of low-carbon publicity.

Retail price increases nonlinearly with the increase in α: In the centralized decision-making mode, the retail price of the product increases significantly with the increase in α. Compared with the decentralized decision-making model, the retail price increases in the centralized decision-making model are larger, which indicates that through coordinated decision-making, the supply chain can better achieve market positioning and profit maximization.

(2) Trends of carbon emission reduction level (e) and low-carbon publicity effort level (g) with consumers' low-carbon sensitivity (α) under decentralized decision-making mode (Figure 2).

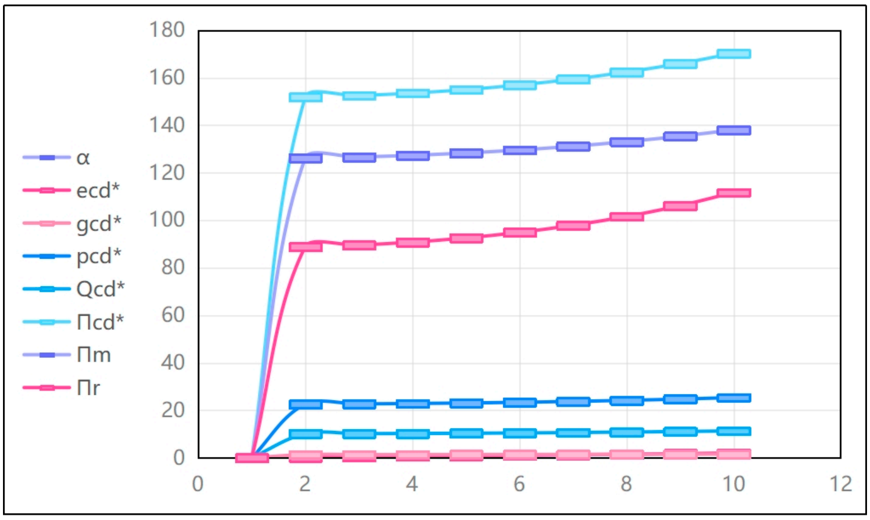

Figure 2. Variation trend of variables with low-carbon sensitivity of consumers (α) under decentralized decision-making.

The level of carbon reduction increases non-linearly with the increase in α: As consumer preference for low-carbon products increases, so does the investment of manufacturers in carbon reduction technologies. This is because manufacturers hope to attract more consumers by improving the low carbon level of their products, thereby increasing the market demand and profits of their products.

The level of low-carbon publicity effort increases nonlinearly with the increase in α: The level of the low-carbon publicity effort of retailers increases with the increase in the low-carbon preference of consumers. This indicates that retailers will invest more resources in low-carbon publicity in the face of higher consumer preferences for low-carbon products to enhance consumer recognition and demand for products.

Retail price increases significantly with the increase in α: With the increase in α, the retail price of the product also increases significantly. This is because, as consumer demand for low-carbon products increases, manufacturers and retailers can realize higher profits by raising prices.

In summary, under the centralized decision-making mode, the level of carbon emission reduction and the level of low-carbon publicity efforts have a greater increase, indicating that the centralized decision-making mode can better integrate supply chain resources, improve the overall low carbon level and publicity effect, and thus more effectively meet the market demand. The retail price in the centralized decision-making mode has a larger increase, indicating that the centralized decision-making mode can better cope with the market changes brought about by the increase in consumers' low-carbon preference and achieve higher profits by coordinating pricing strategies. Through the above analysis, it can be seen that the centralized decision-making mode has greater advantages than the decentralized decision-making mode in improving the overall income of the supply chain when consumers' low-carbon preference increases.

4.2.2. Sensitivity Analysis of the Influence of Market Strategy on Supply Chain Decision-Making

In order to analyze the influence of market strategy on supply chain decision-making, the value range of relevant parameters of market strategy (such as low-carbon publicity sensitivity) β is changed when other parameters are fixed, and its influence on the decision-making of manufacturers and retailers, and the overall profit of the supply chain, is observed. When other parameters are fixed, the value β range of the change is from 0.2 to 1.8, and the change is carried out with 0.2 as the step. The Matlab 2018a tool is used to simulate the decision-making behavior and income of the supply chain under different values (see Tables 5 and 6).

Table 5. Analysis of β's sensitivity to supply chain under centralized decision making.

β	e^*_{cc}	g^*_{cc}	P^*_{cc}	Q_{cc}	Π_{cc}
0.2	0.6	2.5	15	20	300
0.4	0.9	2.8	15.5	20.5	310
0.6	1.2	3.1	16	21	320.5
0.8	1.5	3.4	16.5	21.5	331.5
1	1.8	3.7	17	22	343
1.2	2.1	4	17.5	22.5	355
1.4	2.4	4.3	18	23	367.5
1.6	2.7	4.6	18.5	23.5	380.5
1.8	3	4.9	19	24	394

(1) The change trend of carbon emission reduction level (e) and low-carbon publicity effort level (g) with the effect coefficient of low-carbon publicity effort (β) under centralized decision-making mode (Figure 3).

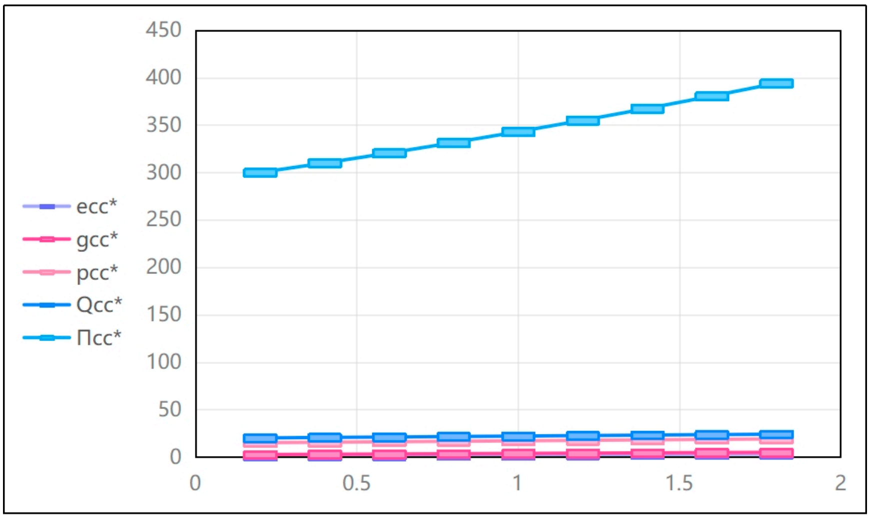

Figure 3. Variation trend of variables under centralized decision-making with consumers' low-carbon sensitivity (β).

The level of carbon emission reduction increases significantly nonlinearly with the increase in β: In the centralized decision-making mode, the investment of manufacturers in carbon emission reduction increases significantly with the increase. Because the overall goal of the supply chain is to maximize profits, manufacturers and retailers, through coordinated decision-making, choose to significantly increase carbon reduction levels at a time when the market is becoming more sensitive to low-carbon propaganda.

The level of low-carbon publicity efforts increases significantly with the increase in β: Under the centralized decision-making mode, retailers also increase the intensity of low-carbon publicity significantly with the increase. This indicates that, under the centralized decision-making mode, coordination among supply chain members can more effectively enhance the effect of low-carbon publicity.

Retail price increases significantly with the increase in β: Under the centralized decision mode, the retail price of the product increases significantly with the increase in β. Compared with the decentralized decision-making model, the retail price increases in the centralized decision-making model are larger, indicating that by coordinating pricing strategies the supply chain can better respond to the changes brought about by the increased sensitivity of the market to low-carbon publicity and achieve higher profits.

Table 6. Analysis of β's sensitivity to supply chain under decentralized decision-making.

β	e^*_{cd}	g^*_{cd}	P^*_{cd}	Q_{cd}	Π_{cd}	Π_m	Π_r
0.2	0.25	1.1	20.5	9.8	140.6	120.3	75.5
0.4	0.35	1.2	21.3	9.9	145.2	125.1	78.2
0.6	0.5	1.35	22	10	150.1	130	80.5
0.8	0.7	1.5	22.5	10.1	155.3	135.2	82.9
1	0.9	1.7	23	10.2	160.8	140.7	85.6
1.2	1.1	1.9	23.5	10.3	166.6	146.4	88.5
1.4	1.3	2.1	24	10.4	172.7	152.3	91.7
1.6	1.5	2.3	24.5	10.5	179.1	158.4	95.2
1.8	1.8	2.5	25	10.6	185.8	164.7	99

(2) The change trend of carbon emission reduction level (e) and low-carbon publicity effort level (g) with the effect coefficient of low-carbon publicity effort (β) under decentralized decision-making mode (Figure 4).

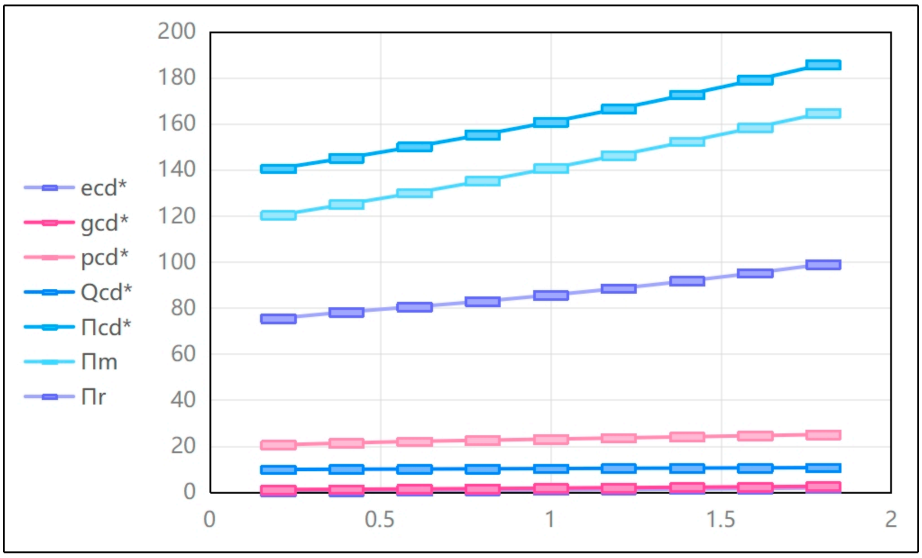

Figure 4. Variation trend of variables under decentralized decision-making with consumers' low-carbon sensitivity (β).

The level of carbon emission reduction increases linearly with the increase in β: With the increase in market strategy sensitivity, the investment of manufacturers in carbon emission reduction technology increases significantly. This indicates that under the decentralized decision-making mode, as the market pays more attention to low-carbon publicity, manufacturers will invest more resources in carbon emission reduction to enhance market demand.

Low-carbon promotional effort level increases linearly as β increases: Retailers' low-carbon promotional effort level also increases as β increases. This suggests that when the market is more sensitive to low-carbon propaganda, retailers will increase their promotional efforts to promote consumers to buy low-carbon products.

Retail price increases significantly with the increase in β: The retail price of the product increases significantly with the increase in β. This shows that under the decentralized decision-making model, as the market becomes more sensitive to low-carbon propaganda, the retail price also increases accordingly to reflect the increase in the added value of the product.

In summary, under the centralized decision-making mode, the level of carbon emission reduction and the level of low-carbon publicity efforts have a greater increase, indicating that the centralized decision-making mode can better integrate supply chain resources, improve the overall low carbon level and publicity effect, and thus more effectively meet the market demand. The retail price in the centralized decision-making mode has a larger increase, indicating that the centralized decision-making mode can better cope with the changes brought about by the increased sensitivity of the market to low-carbon publicity through the coordination of pricing strategies, and achieve higher profits. Through the above analysis, it can be seen that when the market is more sensitive to low-carbon publicity, the centralized decision-making mode has greater advantages than the decentralized decision-making mode in improving the overall revenue of the supply chain.

4.2.3. Sensitivity Analysis of the Interaction Between Consumer Orientation and Market Strategy on Supply Chain Decision-Making

Understanding the sensitivity of the interaction between consumer orientation and market strategies is essential for optimizing supply chain decisions. In decentralized decision-making models, the combined effects of consumer carbon reduction sensitivity (α) and low-carbon marketing sensitivity (β) play a critical role in influencing key decision variables, such as carbon emission reduction (e_i), low-carbon marketing efforts (g_i), product pricing (p_i), market demand (Q_i), and overall supply chain profitability ($\prod_i$). This section conducts a detailed sensitivity analysis of the interaction term ($\alpha\beta$) to identify its impact on the aforementioned variables, providing actionable insights for improving supply chain performance under decentralized strategies (Table 7).

Table 7. Analysis of $\alpha\beta$'s sensitivity to supply chain under decentralized decision-making.

$\alpha\beta$	e_i	g_i	p_i	Q_i	$\prod_i$
0.04	0.294	8.125	183	488	29.41
0.16	0.891	9.212	190.96	505.12	89.17
0.36	1.8	10.354	200.48	526.26	179.49
0.64	3.075	11.628	211.695	551.69	320.46
1	4.77	13.061	225.08	582.34	545.1
1.44	6.93	14.68	240.975	619.65	904.01
1.96	9.72	16.598	260.28	665.16	1497.23
2.56	13.257	18.814	283.975	721.45	2487.49
3.24	17.82	21.56	313.5	791.76	4199.06

The results of this sensitivity analysis demonstrate that the interaction between consumer orientation ($\alpha\beta$) and market strategies has a profound impact on supply chain decision-making (Figure 5). By leveraging consumer preferences for low-carbon products and effective marketing, supply chain participants can enhance their profitability while simultaneously promoting sustainability. These findings highlight the importance of tailoring both production and promotional strategies to align with consumer sensitivities in decentralized decision-making environments.

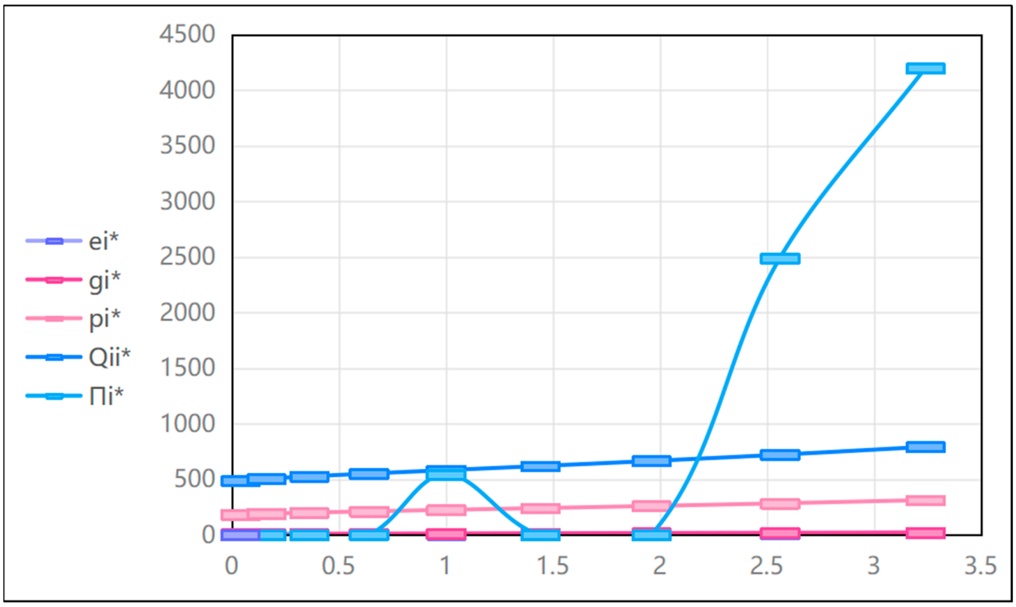

Figure 5. Sensitivity analysis of the interaction between consumer orientation and market strategy on supply chain decision-making ($\alpha\beta$).

5. Discussion

5.1. Mechanisms for Achieving Low-Carbon Innovation in Supply Chains

The results of this study also confirm Tang's findings. Through his research on the Stackelberg game model based on co-operative incentives in large-scale group decision making, Tang confirmed that co-operative incentive mechanisms can significantly optimize the level of coordination among decision makers, thus achieving higher economic and environmental benefits in the supply chain [14]. Based on the model analysis above, the decision-making behaviors and equilibrium solutions of supply chain companies differ under centralized and decentralized strategies, which, in turn, affect both consumer surplus and the economic profit of the supply chain. The equilibrium retail price, carbon reduction level, and low-carbon marketing effort level differ between the centralized and decentralized strategies [17]. Under centralized strategies, manufacturers and retailers work collaboratively to align goals, optimize resource allocation, and implement co-operative strategies. This alignment fosters a more efficient allocation of resources and ensures that decisions regarding pricing, carbon reduction, and marketing efforts are made with a unified objective: maximizing both economic and environmental outcomes. In contrast, decentralized strategies are characterized by independent decision-making, where manufacturers and retailers prioritize their own profits. This often results in suboptimal coordination, limiting the ability to achieve broader low-carbon goals. Collaborative efforts in centralized strategies, however, not only enhance economic outcomes but also promote consumer adoption of low-carbon products, creating a positive feedback loop between supply chain innovation and consumer behavior. This illustrates that through effective incentive mechanisms and co-operative strategies, supply chain companies in a centralized decision-making model can enhance both economic and environmental outcomes, thereby improving overall consumer welfare [26]. In the process of promoting low-carbon innovation, supply chain companies should prioritize collaboration to jointly expand the market for low-carbon products and shape consumer preferences for these products (see Figure 3). This highlights the critical role of sustainable supply chain practices in fostering long-term value creation and reducing environmental footprints.

Moreover, the role of government policy interventions, such as green subsidies and carbon taxes, cannot be overlooked. Policies that incentivize carbon reduction efforts and sustainable practices can help align the interests of decentralized supply chain participants, fostering greater collaboration and enabling the supply chain to achieve both economic and environmental goals. For example, subsidies reduce the effective costs of low-carbon production and marketing, encouraging investments in sustainability, while carbon taxes discourage environmentally harmful practices.

5.2. Manufacturer's Low-Carbon Innovation

The results of this study validate Su's research. Su's research on the impact of consumer preferences on low-carbon decision-making and coordination strategies in supply chains confirms that centralized strategies can effectively improve carbon emission reduction level and market competitiveness by optimizing resource allocation and strengthening supply chain collaboration. In addition, the study also shows that consumer preference for low-carbon products significantly drives low-carbon investment and marketing efforts of manufacturers and retailers, thus forming a positive feedback loop between supply chain innovation and consumer behavior, consistent with the conclusions of this study [1]. Manufacturers in the supply chain are primarily responsible for the research, development, and production of low-carbon products. Low-carbon innovation can be achieved in two key ways: First, manufacturers can reduce carbon emissions in their products through technological research and development (R&D), where R&D investment directly affects the performance and market competitiveness of low-carbon products [20]. Second, once breakthroughs in low-carbon technology are made, manufacturers can begin producing low-carbon products that meet both market demand and environmental standards.

Under the centralized strategy, manufacturers and retailers collaborate to optimize the allocation of resources for low-carbon R&D and production, aiming to maximize the overall profit of the supply chain while simultaneously reducing carbon emissions. In contrast, under the decentralized strategy, manufacturers make independent decisions, adjusting production costs and R&D investments to maximize their own profits [29]. This shows that centralization facilitates resource-sharing and alignment of goals across supply chain participants, supporting the broader objectives of sustainable development.

The interaction between consumer orientation and policy interventions is particularly critical for manufacturers. As consumer sensitivity to carbon reduction increases, manufacturers are further incentivized to invest in low-carbon R&D. Policies such as green subsidies amplify this effect, creating a supportive environment for sustainable innovation.

5.3. Retailer's Low-Carbon Marketing

Retailers are instrumental in promoting low-carbon awareness and encouraging low-carbon consumption among consumers through various marketing strategies. First, retailers can stimulate sales and shape consumer preferences for low-carbon products through market development and promotional activities [18]. Second, retailers can use advertising, promotions, and other marketing efforts to highlight the environmental benefits of low-carbon products, thus increasing consumer recognition and demand. Retailers also conduct market research and expand distribution channels to identify and grow the market for low-carbon products [30].

Under the centralized strategy, retailers collaborate closely with manufacturers to develop marketing strategies that maximize the promotion and sales of low-carbon products, ensuring a coordinated effort to increase market penetration. In the decentralized strategy, retailers make independent decisions regarding marketing investments and strategies, aiming to maximize their own profits. However, the lack of coordination may limit the full potential for driving low-carbon consumption across the supply chain, indicating that centralization may be more effective in achieving large-scale environmental goals.

The interaction between consumer orientation and retailer marketing strategies is particularly pronounced. As consumers become more responsive to low-carbon marketing, retailers are incentivized to enhance their promotional efforts. This interaction effect creates a virtuous cycle, where increased consumer awareness drives higher demand, which in turn encourages greater marketing investments.

5.4. Consumer Preferences for Low-Carbon Products

Consumer preferences for low-carbon products are the ultimate goal of low-carbon innovation in supply chains. These preferences can be developed in two primary ways: First, once consumers recognize the environmental benefits of low-carbon products, they are more likely to choose such products over traditional alternatives [3]. Second, once consumers develop trust in and loyalty to a brand, they are likely to continue purchasing low-carbon products from that brand, contributing to long-term market demand for sustainable products [5].

Wang's study confirms this conclusion. Studies have shown that optimizing financing decisions between manufacturers and retailers can improve overall supply chain profits while achieving low-carbon goals. This result further validates the important role of the combination of centralized decision-making and policy incentives (such as green subsidies) in optimizing supply chain resource allocation and promoting low-carbon innovation in this study [15]. Policy interventions play a key role in accelerating this process. For instance, subsidies for low-carbon products can lower retail prices, making these products more accessible to consumers. Similarly, carbon taxes can increase the cost of traditional, high-emission products, steering consumers toward more sustainable alternatives. By aligning consumer incentives with supply chain goals, policies create a supportive ecosystem for low-carbon innovation.

The interaction effect between consumer preferences, market strategies, and policy interventions underscores the importance of a holistic approach to supply chain management. By simultaneously addressing consumer behavior, supply chain practices, and policy frameworks, companies can achieve meaningful progress in reducing their environmental impact while enhancing economic performance.

6. Conclusions

6.1. Research Conclusions

This study explores the mechanisms for achieving low-carbon innovation in supply chains, focusing on consumer orientation and market strategies under centralized and decentralized decision-making models. The key findings are summarized as follows:

6.1.1. Consumer Orientation as a Key Driver

Increasing consumer preferences for low-carbon products significantly drives manufacturers' investments in carbon reduction technologies and retailers' low-carbon marketing efforts, highlighting the critical role of consumer demand in promoting low-carbon innovation.

6.1.2. Market Strategies' Influence

Market strategies, particularly sensitivity to low-carbon marketing, shape the decision-making of manufacturers and retailers. Centralized models foster coordinated resource allocation, achieving superior economic and environmental outcomes compared to decentralized models.

6.1.3. Advantages of Centralized Decision-Making

Centralized strategies enable better integration of resources and coordination among supply chain members, leading to greater carbon reduction, more effective marketing, and higher overall profitability.

6.1.4. Maximization of Supply Chain Profit

Through collaborative pricing and investment decisions, centralized models align environmental and economic goals, maximizing profitability while driving sustainable practices in supply chains.

6.1.5. Interaction Effects and Green Subsidies

The study identifies the critical interaction effects between consumer orientation and market strategies, as well as the role of policy incentives. Green subsidies significantly reduce the effective costs of carbon reduction and marketing efforts, encouraging manufacturers and retailers to invest in sustainable practices. These subsidies, when combined with growing consumer preferences for low-carbon products, create a virtuous cycle that drives innovation and market expansion. The interplay of these factors highlights the importance of integrating consumer preferences, market strategies, and policy interventions to achieve comprehensive and sustainable outcomes in supply chains.

6.2. Management Strategies

To achieve low-carbon innovation, the following strategies are recommended:

(1) Collaborative Innovation: supply chain members should foster close co-operation and shared strategies to optimize resource allocation and drive low-carbon innovation.
(2) Low-Carbon Marketing and Education: retailers must enhance efforts to promote low-carbon products and educate consumers, stimulating demand and encouraging sustainable consumption.
(3) Life-Cycle Management: manufacturers should adopt end-to-end low-carbon management practices across design, production, transportation, and recycling stages
(4) Technology Integration: advanced technologies like IoT and AI can optimize emissions and enhance efficiency throughout the supply chain.
(5) Green Standards: industry-wide green supply chain standards can guide companies in implementing low-carbon practices systematically.
(6) Policy Incentives: governments should provide subsidies, tax reductions, and other incentives to encourage low-carbon investments and innovation.

6.3. Research Limitations and Future Prospects

This study highlights the importance of advancing low-carbon innovation in supply chains but lacks validation through real-world data, relying primarily on theoretical models and numerical simulations. To address this limitation, future research should incorporate empirical case studies from industries like automotive, consumer goods, or energy to test the applicability of the proposed frameworks. Furthermore, dynamic cost and market factors, such as fluctuating raw material prices and consumer behavior trends, should be modeled to better reflect real-world conditions. Policy impacts, including green subsidies and carbon taxes, must also be quantified through simulations or cross-regional analyses to understand their role in shaping supply chain decisions. Finally, considering regional differences in consumer preferences and policy environments is crucial, as low-carbon innovation drivers vary between developed and emerging economies. By adopting an interdisciplinary approach and leveraging advanced tools like AI and big data, future research can provide deeper insights and actionable strategies for achieving sustainable and adaptable supply chains.

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Institutional Review Board Statement: This review was primarily conducted by members of the Academic Committee of Guangdong University of Science and Technology. After discussion by the Academic Committee, this research has passed the ethical review.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: This study does not involve any datasets. All theoretical models and numerical simulations presented in this research are derived from analytical frameworks and do not rely on empirical data. Further details regarding the models can be provided by the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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