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Research Article

Integrated Optimization of Sustainable Transportation and Inventory with Multiplayer Dynamic Game under Carbon Tax Policy

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Growth in environmental sustainability has prompted the logistics industry to seek sustainable development, and carbon tax policies are considered an effective approach to reducing carbon emissions. This study investigates the optimization of sustainable transportation and inventory under a carbon tax policy and explores effective methods for coordinating the interests of governments and enterprises. The results can provide insights into sustainable logistics for decision-making by enterprises and policy-making by governments. We first examine a Stackelberg game model and design an iterative solution to optimize sustainable transportation and inventory under the carbon tax policy. We then establish a three-stage dynamic game model to optimize the wholesale price, carbon tax rate, and proportion of sustainable investment shared by the government. Furthermore, we perform a simulation to identify the optimal solution of the three-stage game, and we compare the simulation results with a numerical example. The results indicate that a carbon tax policy can improve social welfare and the sustainability of transportation and inventory but could hinder corporate profits. An appropriate sustainable investment-sharing strategy could compensate for the shortcomings of the carbon tax policy and result in positive outcomes for governments and enterprises.

1. Introduction

With increasingly severe environmental pollution worldwide, people have gradually become aware of the importance of sustainable development. An increasing number of countries are taking measures to control greenhouse gas emissions, and organizations and individuals are undertaking environmental-protection actions to reduce carbon emissions [1]. To address pollution, developed and developing countries have implemented regulations aimed at reducing carbon emissions [2]. A carbon tax is one such emissions-reduction regulation that has been widely implemented to encourage companies to reduce their carbon emissions [3]. Carbon taxes have been adopted in Australia, Japan, Denmark, Austria, Finland, and Ireland [2]. In Australia, the carbon tax was implemented in 2011, with a rate of AU\$23 per ton of carbon in 2012 [4]. A carbon tax increases the cost of operations [5], which encourages enterprises to increase their sustainable investments. Dong et al. [6] indicated that sustainable investment can reduce the carbon emissions of manufacturers, and both manufacturers and sellers can benefit from it. Sustainable investment improves not only environmental sustainability but also a firm's long-term profitability and competitiveness [7]. For example, in 2007, Marks & Spencer invested £200 million in carbon-reduction efforts; moreover, Walmart has reduced its carbon emissions by 667,000 m^3 after requiring its 60,000 suppliers to reduce their packaging by 5% [8].

Given this context, enterprises are motivated to optimize their supply chains and invest in clean-energy technologies to reduce carbon emissions [9]. Sustainable supply chain management is a growing concern because production and logistics activities lead to waste and pollution [10]. The logistics industry consumes energy and fossil fuels and is a major source of carbon emissions in the supply chain [11]. A survey of the supply chain operations of 2,500 large enterprises revealed that logistics-induced emissions exceeded 20% of total supply chain emissions [12]. This result demonstrates that logistics has a significant negative impact on both environmental sustainability and economic growth. To protect the environment, governments should implement strict environmental-protection policies and encourage sustainable investment in the logistics industry [13, 14].

Transportation and inventory management are the main sources of carbon emissions in the logistics industry [15]. Transportation is the largest source of carbon emissions. Inventory control determines logistics factors, such as inventory level, warehousing activities, and transportation frequency [12], which are crucial for decision-making in supply chain operations. In Europe, transportation is the sector with the second highest carbon emissions (the energy supply sector has the highest), accounting for 23% of total carbon emissions [5]. Transportation and inventory are the two most critical elements of logistics in terms of both economics and ecology. The efficient management of a logistics system requires an integrated approach that combines various logistics functions [16]. Furthermore, few studies have explored the optimization of sustainable investment through the integration of transportation and inventory decision-making on a global scale. Therefore, research on integrating decision-making in sustainable transportation and inventory would facilitate the reduction of carbon emissions in the logistics industry and promote sustainable development.

This study investigated the relationships between government, suppliers, and retailers (Figure 1). Governments adopt carbon tax policies to optimize social welfare. Suppliers and retailers make decisions concerning transportation and inventory management, respectively, with the aim of maximizing profits. Carbon emissions in transportation and inventory management have been analyzed, but carbon emissions due to other activities in the supply chain have not been considered. Therefore, we investigated the following research questions:

(1) Under a carbon tax, how can suppliers and retailers maintain sustainable levels of transportation and inventory?

(2) How do governments set carbon tax rates and incentives?

(3) What effect does a carbon tax have on supply chain performance, and how can government and enterprise objectives be harmonized?

This study aimed to achieve three specific goals: (1) to establish an integrated optimization model for sustainable levels of transportation and inventory under a carbon tax; (2) to construct a multiplayer dynamic game model to determine the optimal carbon tax rate and the sustainable investment-sharing strategy; and (3) to solve this multiplayer dynamic game model through a MATLAB simulation and to explore the effect of a carbon tax on sustainable transportation and inventory, enterprise profits, and social welfare.

The remainder of this paper is organized as follows. Relevant studies are discussed in Section 2. Section 3 proposes assumptions and details of the notations used. Section 4 presents the model for sustainable transportation and inventory optimization under a carbon tax, along with an analysis of and solution to the model. A three-stage game model, which was designed to optimize the carbon tax rate and sustainable investment-sharing strategies, is presented in Section 5. Section 6 provides the results of simulations performed to solve the three-stage model numerically, along with an analysis of the effect of a carbon tax on decision-making. Conclusion is presented in Section 7.

2. Literature Review

Numerous studies have explored sustainability in the supply chain. Those highly related to the present topic were divided into three categories according to the topic: carbon tax, integrated environmental optimization of transportation and inventory management, and sustainable investment in the supply chain.

2.1. Carbon Tax. A carbon tax is an effective approach to mitigate climate change and is one of the two main instruments for redesigning the supply chain (the other being cap-and-trade programs) [2]. A succession of studies have focused on the effect of a carbon tax on emission reduction. Shu et al. [17] reported that a carbon tax can place a heavier financial burden on companies to meet certain emission targets than other carbon-reduction policies can. Chen and Nie [18] demonstrated that a specific number of carbon taxes in the production process can improve social welfare, whereas consumption and redistribution reduce social welfare. Moreover, Olsen et al. [19] indicated that if a carbon tax is implemented after properly analyzing its impact, its revenue can be used to support government investment in projects that reduce emissions. Ma et al. [20] argued that economists and policymakers prefer a carbon tax because its implementation requires less management than that of other carbon-reduction policies. However, Xie et al. [21] indicated that a carbon tax harms economic growth because it inevitably entails companies incurring additional costs. Many studies have investigated the significant impact of a carbon tax on supply chain performance. Bao and Zhang [22] developed a mixed linear programming model to explore sustainable procurement relationships in a supply chain under a carbon tax scheme. Fahimnia et al. [4] proposed a tactical supply-planning model that optimizes carbon emissions and economic targets under a carbon tax. Xin et al. [23] discussed the problem of sustainably scheduling a shuttle tanker fleet with variable tanker speed under a carbon tax. Wang et al. [24] examined decisions about a carbon tax in decentralized and centralized supply chains by using the Stackelberg game model. They proved that a carbon tax in a decentralized supply chain should be higher than that in a

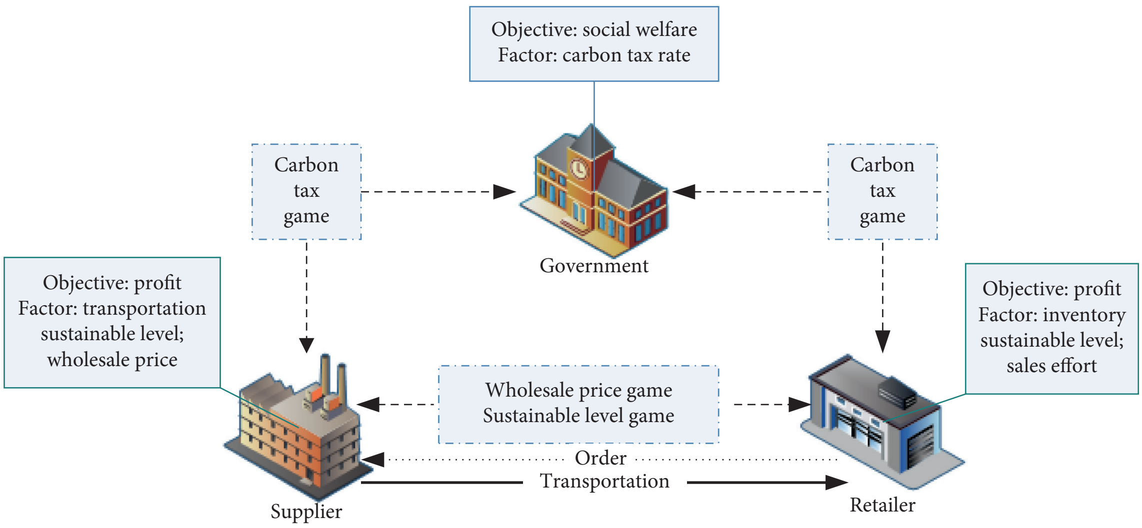

Figure 1: Relationships of the multiplayer game.

centralized supply chain. Wang et al. [25] derived the optimal level of supply chain emission reduction with stochastic demand under a carbon tax. They reported that optimal emission reductions gradually increased with an increase in the carbon tax rate. Ding et al. [26] developed a diffusion model of energy technology to explore the possible impacts of various carbon tax conditions on the diffusion of energy technologies in China. Alizadeh et al. [27] studied the impact of the uncertainty of the carbon tax rate on emissions in a supply chain. Their results demonstrated that increasing the uncertainty of the carbon tax rate from 0 to 30 reduced total network emissions by 2.8%. However, integrating sustainable investment into logistics operating decisions has not been considered in most of these studies.

2.2. Integrated Environmental Optimization of Transportation and Inventory Management. Employees usually make decisions regarding inventory management and transportation in an organization. Collaboration is the optimal supply chain strategy [28]. The interaction between inventory parameter decisions and transportation choices indicates that, to optimize transportation and inventory management, they must be integrated. Integrated optimization problems can be categorized as strategic or tactical. Gaur and Fisher [29] divided integration optimization problems into those with finite and infinite periods. Four main types of logistics networks exist, namely, one-to-one, one-to-many, many-to-one, and many-to-many [30]. This study focused on one-to-one networks. One-to-one networks have not a routing problem, whereas the other three network types do.

Recently, increasing numbers of scholars have included carbon emission factors in integrated decision models for transportation and inventory management. Economic order quantity (EOQ) models with various carbon emission regulations are the predominant tool employed in most studies on transportation and inventory management. Bonney and Jaber [31] presented an EOQ model associated with carbon emissions and waste produced by transportation and inventory operations. Tang et al. [32] integrated emissions, transportation costs, and inventory costs into the (R, Q) policy with stochastic demand. Hovelaque and Bironneau [33] considered the carbon emission problem in an EOQ model with demand dependent on price and carbon emissions. Hua et al. [34] constructed an EOQ model for a carbon cap-and-trade policy and analyzed the trends of replenishment decisions, costs, and carbon emissions with changes in the carbon trading price. Chen et al. [35] proposed a condition for achieving a carbon emission-reduction target by adjusting the order quantity based on an EOQ model. Gautam et al. [36] integrated defect management into a sustainable supply chain model to jointly optimize the number of shipments and quantities of orders and backorders. Konur and Schaefer [12] developed integration models for transportation and inventory management for four carbon policies. They compared and analyzed the impacts of these policies on the optimal order quantity. Wang et al. [39] studied the optimization of refined oil distribution under a carbon tax. Their results revealed that a carbon tax effectively reduced the carbon emissions due to refined oil distribution. Reddy et al. [38] established a multiperiod reverse logistics network design model and analyzed the impact of a carbon tax on the optimal decisions. Konur and Schaefer [12] examined the EOQ model for less-than-truckload and truckload shipping under cap-and-offset, cap-and-trade, carbon cap, and carbon tax policies. Micheli and Mantella [5] designed a comprehensive model of transportation and inventory under the cap, cap-and-offset, cap-and-trade, and carbon tax. They involved a comprehensive emission model with vehicles.

In-depth research has been conducted on optimizing the integration of transportation and inventory management. In such research, the main decision-making objectives are to optimize transportation and inventory management under certain economic and social goals. Studies on environmental factors have focused on the impact of carbon emissions and carbon-reduction policies on transportation and inventory integration decisions. The present study extends the literature by introducing sustainable investment factors into the decision-making model for transportation and inventory integration, and we focused on the optimal decisions to reach sustainable levels of emissions due to transportation and inventory.

2.3. Sustainable Investment in a Supply Chain. Supply chain emission reduction has become a critical, theoretical, and practical topic, with numerous studies discussing it and proposing investment in clean technologies to reduce carbon emissions (i.e., sustainable investment). Several studies have focused on the effectiveness of sustainable investment. Drake and Spinler [37] noted that the effectiveness of clean technologies in sustainable economic development should not be underestimated. Shi et al. [40] analyzed the comprehensive effects of power structures and sustainable investment in the supply chain on the economy and environment. Su et al. [41] developed a pricing decision model to explore the effects of government subsidies on optimal decisions for sustainable supply chain management under various government subsidies and power structures. Scholars have often studied sustainable investment decision-making under multiple carbon-reduction policies. Benjaafar et al. [42] studied the impact of clean technologies on carbon reduction. The results indicated that a carbon cap-and-trade regulation can effectively encourage companies to adopt clean technologies if the benefits of a clean technology are substantial. Krass et al. [43] believed that increasing taxes may prompt companies to switch to clean technology when opting for emission control technology. If the input cost of clean technology is compensated for, the negative environmental impact will be eliminated and the tax will have proved effective. Chen [44] explored the impact of a carbon tax on the choice of energy-saving technologies by enterprises under market competition. Chen's results demonstrated that clean and conventional technologies can coexist and that companies choose technologies according to the tax rate. Shifting to clean technology is not always the optimal choice when dealing with a rising tax rate. Drake et al. [45] compared the impacts of a carbon tax and a carbon cap-and-trade policy on the corporate sustainable technology choice and capacity decisions, and their results revealed that the expected profit under a cap-and-trade policy was higher than that under a carbon tax.

With the deepening of research into sustainable investment, integrating sustainable investment into supply chain activities such as procurement, production, and inventory has received increasing attention. Toptal et al. [46] introduced retailers' sustainable investments into an EOQ model and constructed joint decisions for sustainable investment and inventory management under carbon cap and cap-and-trade policies. The model revealed that sustainable investment can simultaneously reduce carbon emissions and costs. Dong et al. [6] studied the sustainable investment problem under a carbon cap-and-trade policy and constructed a decision-making model for decentralized coordination and centralized control of a supply chain. The conclusions indicated that sustainable investment substantially influenced the optimal supply chain strategy. Based on the results of Dong et al. [6], Cheng et al.[8] introduced big data to the sustainable investment decision-making model. Their results revealed that adopting big data was not always the optimal choice for retailers. Moreover, they showed that whether manufacturers increase sustainable investment depends on the service level set by the retailer.

With continual advancements in sustainability, consumers are increasingly concerned about the environmental impact of goods, and this is referred to as consumer environmental awareness [5]. Consumer environmental awareness has often been integrated into the supply chain optimization model along with sustainable investment. For example, Zhang and Liu [47] examined pricing strategies in a three-level supply chain where demand was relative to the environmental impact of products. Du et al. [48] proposed a carbon-sensitive demand function to investigate the impact of consumers' preferences for reducing carbon emissions on a supply chain, and they designed various supply chain coordination contracts. Consumer environmental awareness has two main impacts on the sustainable supply chain model. The first is the impact on market demand; when carbon emissions decrease, market demand increases [6, 8]. The second is the impact on prices; when consumer environmental awareness increases, low-carbon products receive more recognition, even among companies with higher prices [48]. The higher consumer environmental awareness is, the greater is the willingness of consumers to pay for sustainable products [49]. Consumer environmental awareness motivates manufacturers to produce more sustainable products, but this does not necessarily mean higher profits for manufacturers [50].

Toptal et al. [46], Dong et al. [6], and Cheng et al. [8] have conducted similar investigations into retailers' perspectives regarding inventory replenishment and sustainable investment. Dong et al. [6] and Cheng et al. [8] have investigated sustainable investments in production. By contrast, the present study investigated sustainable investments in logistics. Toptal et al. [46] analyzed sustainable investment in inventory management, whereas we considered sustainable investments in both transportation and inventory management. Moreover, Toptal et al. [46] explored deterministic demand. By contrast, the present study included the sales effort factor and sustainable investment in a random demand function to harmonize the optimization model with the real enterprise situation. Table 1 presents the studies related to the present paper.

3. Model Assumptions and Notation

In this study, we considered a supply chain consisting of one supplier and one retailer selling a single product. Over a single cycle, the supplier sells the product to the retailer at the wholesale price, and the supplier is responsible for shipping the product from its factory to the retailer's warehouse. The retailer is responsible for product ordering and inventory management, and the retailer sells the product

Table 1: The literature positioning of this paper.

Papers	Carbon emission	Sustainable investment	Carbon tax	Integrated optimization of transportation and inventory
Fahimnia et al. [4], Wang et al. [24], Wang et al. [25]	✓		✓	
Webb and Larson [51], Gaur and Fisher [29]				✓
Bonney and Jaber [31], Hua et al. [34], Tang et al. [32]	✓			✓
Konur and Schaefer [12], Micheli and Mantella [5], Wang et al. [37]	✓		✓	✓
Toptal et al. [46], Dong et al. [6], Cheng et al. [8]	✓	✓		
This paper	✓	✓	✓	✓

to consumers at the market retail price. In a carbon tax scenario, decision-making involves two consecutive steps. In the first step, the supplier determines the appropriate extent of sustainable investment for transportation given the goal of maximizing profit. In the second step, given a sustainable level of transportation, the retailer determines the sustainable inventory level and order quantity for the product. The notations used in the models are summarized in Table 2. The models are limited by the following assumptions:

(1) A supplier trades with a retailer during a single period. The retailer can only order once during the period. If the retailer's order quantity exceeds market demand, the leftover stock is disposed at the unit salvage value v. Without loss of generality, we assume that $v < C_s$, where C_s is the unit production cost. Moreover, we assume that the explicit shortage cost is zero if the market demand exceeds the retailer's order quantity [6]. When market demand exceeds the retailer's order quantity, the retailer sells out its inventory; urgent orders are not allowed.

(2) The sustainability level is a dimensionless index that measures carbon emissions. The higher the sustainability level is, the lower are the carbon emissions. Assume that the sustainable transportation level $s_p \in [0, (a_p/b_p)]$ and the sustainable inventory level $s_l \in [0, (a_l/b_l)]$. When $s_p = 0$, carbon emitted per unit of the product for transportation is a_p. When $s_l = 0$, carbon emitted per unit of the product for transportation is a_l. Carbon emitted per unit of the product for inventory is $a_p - b_p s_p$. Carbon emitted per unit of the product for inventory is $a_l - b_l s_l$.

(3) Sales effort x is a comprehensive index that reflects the retailer's efforts to promote market demand through activities such as advertising, services, and sales promotions. Let $x \geq 0$; we assume that $f'(x) > 0$, $f''(x) < 0$, $g'(x) > 0$, and $g''(x) \geq 0$, where $f(x)$ represents the demand generated by sales effort and $g(x)$ represents the costs incurred by sales effort. The assumption indicates that $f(x)$ and $g(x)$ are increasing functions. However, the rate of demand increase decreases with x, and the rate of cost increase is zero or increasing with x [52].

(4) Product demand D is uncertain; it depends not only on the retailer's sales effort x, the sustainable inventory level s_l, and the sustainable transportation level of the supplier s_p but also on the market's random demand factor ξ, as expressed in the following: $D(x, s_p, s_l) = f(x) + \beta(s_p + s_l) + \xi$. Moreover, β is the coefficient of the effect of sustainability on increasing demand, ξ is the random demand with mean μ, and the probability density function and probability distribution function are $\phi(y)$ and $F(y)$, respectively. Furthermore, $\beta(s_p + s_l)$ represents the demand generated by the sustainable transportation level s_p and sustainable inventory level s_l. If $\beta > 0$, then the sustainability level has a positive effect on the demand. When $s_p = 0$ and $s_l = 0$, the demand generated by the sustainability level is zero. The maximum values of demand generated by s_p and s_l are $\beta a_p/b_p$ and $\beta a_l/b_l$, respectively.

(5) The higher the sustainability level is, the higher is the cost of sustainable investment and the faster is the cost increase. Similar to [6, 8, 53], we assume that the sustainable investment costs for transportation and inventory are quadratic functions, specifically $\delta_l s_l^2/2$ and $\delta_p s_p^2/2$, respectively, where δ_l and δ_p are the sustainable investment coefficients for transportation and inventory, respectively. In practice, the costs of sustainable investment are usually high. Therefore, we assume that δ_l and δ_p are sufficiently high that $\delta_l \geq 2rb_l\beta$ and $\delta_p \geq 2rb_p\beta$, where r is the carbon tax rate. Otherwise, the lower bound and upper bound of the sustainability level interval are the optimal values of s_p and s_l; that is, $s_p =$ 0 or (a_p/b_p) and $s_l = 0$ or (a_l/b_l). The assumption is that $\delta_l \geq 2rb_l\beta$ and $\delta_p \geq 2rb_p\beta$ can avoid these simple solutions [6].

4. Optimization Model for Sustainable Transportation and Inventory under a Carbon Tax

Based on the Stackelberg game between the supplier and the retailer, this paper uses a backward sequential decision-making approach. First, the retailer's sales effort, sustainable

Table 2: Notations.

Notation	Meaning
p	Market price
w	Wholesale price
C_s	Unit production cost
C_p	Unit transportation cost
C_l	Unit inventory cost
v	Unit salvage cost
Q	Retailer's reorder quantity
D	Demand function
L	Service level
x	Sales effort
s_p	Sustainable transportation level
s_l	Sustainable inventory level
β	Coefficient of the effect of sustainability on demand
δ_l	Coefficient of sustainable inventory investment
δ_p	Coefficient of sustainable transportation investment
a_p	Emissions when sustainable transportation level is zero
b_p	Coefficient of the effect of sustainability on transportation emissions
a_l	Emissions when sustainable inventory level is zero
b_l	Coefficient of the effect of sustainability on inventory emissions
r	Carbon tax rate
θ	Coefficient of the effect of environmental damage on environmental utility
π_R	Retailer's profit function
π_V	Supplier's profit function
SW	Social welfare
U_{ec}	Economic utility
U_{en}	Environmental utility

inventory level, and order quantity are determined on the basis of the sustainable transportation level of the supplier. Subsequently, we solve the supplier's problem according to the retailer's decision-making plan and obtain the optimal sustainable transportation level.

4.1. Decision-Making under a Carbon Tax

4.1.1. Retailer's Decision. For a given sustainable transportation level, the retailer maximizes the expected profit by optimizing the order quantity, sales effort, and inventory sustainability level. Under a carbon tax policy, enterprises are required to pay a tax related to carbon emissions generated during their operations [21]. When considering the carbon tax policy, the expected profit of retailers is calculated as follows:

$$\begin{aligned}\pi_R = E\Big[&p\min(Q,D) - (w+c_l)Q - g(x) - \frac{\delta_l s_l^2}{2} \\ &+ v(Q-D)^+ - r(a_l - b_l s_l)Q\Big].\end{aligned} \tag{1}$$

In equation (1), the first term is the income of the sales product, the second term is the purchasing cost of the product from the supplier and the logistics cost, the third term is the sales cost of the retailer, the fourth term is the sustainable investment cost in the inventory, the fifth term is the remaining cost, the sixth term is the carbon tax cost, and $(a_l - b_l s_l)Q$ is the carbon emissions due to inventory. Based on equation (1), when considering the carbon tax, the retailer's sales effort x is affected by the sustainable inventory level s_l. The retailer must integrate decisions related to the sales effort x and the sustainable inventory level s_l, which add complexity to the decision process.

Given x, s_p, and s_l, the first and second derivatives of equation (1) with respect to Q yield the following proposition.

Proposition 1. *Under the carbon tax, the retailer's optimal order quantity, denoted by Q^*, for given x, s_p, and s_l, is as follows:*

$$Q^* = f(x) + \beta\left(s_p + s_l\right) + F^{-1}\left(\frac{p - w - c_l - r(a_l - b_l s_l)}{p - v}\right). \tag{2}$$

The optimal order quantity Q^* increases with an increase in the remaining cost v and decreases with increases in the market price p, the wholesale price w, and the inventory cost c_l. The first derivatives of Q^* with respect to x and s_p are shown in equation (3). These equations indicate that the optimal order quantity Q^* increases with increases in x and s_p.

$$\begin{aligned}\frac{dQ}{dx} &= f'(x),\\ \frac{dQ}{ds_p} &= \beta.\end{aligned} \tag{3}$$

By substituting Q^* into equation (1) and incorporating the first-order and second-order conditions of equation (1) with respect to x and s_l, we obtain Propositions 2 and 3, respectively.

Proposition 2. *Under the carbon tax, the retailer's optimal sales effort, denoted by x^*, for given s_l, should satisfy the following equation:*

$$\left(p - w - c_l - r\left(a_l - b_l s_l\right)\right) f'\left(x^*\right) = g'\left(x^*\right). \tag{4}$$

Proposition 3. *Under the carbon tax, the retailer's optimal sustainable inventory level, denoted by s_l^*, for given x, is as follows:*

$$s_l^* = \frac{\left(p - w - c_l - ra_l\right)\beta + rb_l\left(f(x) + \beta s_p\right)}{\delta_l - 2rb_l\beta}. \tag{5}$$

4.1.2. Supplier's Decision. The supplier supplies products according to the retailer's order quantity and determines the sustainable transportation level. When considering the carbon tax cost, the supplier's profit function is shown in equation (6), and $(a_p - b_p s_p)Q$ represents the carbon emissions due to transportation:

$$\pi_V = \left(w - c_s - c_p\right)Q - r\left(a_p - b_p s_p\right)Q - \frac{\delta_p s_p^2}{2}. \tag{6}$$

By substituting the retailer's optimal order quantity Q^* into equation (6), we can obtain Proposition 4 based on the first-order and second-order derivatives of equation (6) with respect to s_p.

Proposition 4. *Under the carbon tax, the supplier's optimal sustainable transportation level for given x and s_l is as follows:*

$$s_p^* = \frac{\left(w - c_s - c_p - ra_p\right)\beta + rb_p\left(f(x) + \beta s_l + F^{-1}\left(\left(p - w - c_l - r\left(a_l - b_l s_l\right)\right)/(p - v)\right)\right)}{\delta_p - 2rb_p\beta}. \tag{7}$$

Proposition 4 indicates that s_p^* monotonically increases with increases in w and β and monotonously decreases with increases in c_s, c_p, and δ_p.

4.2. Analysis of Decision Results. The decision model results support the following conclusions.

Corollary 1. *The carbon tax reduces the retailer's sales effort s_l.*

When $r = 0$ (i.e., no carbon tax policy), the retailer's optimal sales effort, denoted by x^{0*}, should satisfy equation (8). Comparing equations (4) and (8) reveals that $x^* < x^{0*}$. Therefore, increases in the carbon tax rate reduce the retailer's profits per product unit, thus reducing sales effort and enthusiasm [2, 18].

$$\left(p - w - c_l\right) f'\left(x^{0*}\right) = g'\left(x^{0*}\right). \tag{8}$$

Corollary 2. *Under the carbon tax, increasing the retailer's sustainable inventory level s_l can increase its sales effort x^*.*

Equation (4) illustrates that x^* increases monotonically with increase in s_l. This means that the higher the sustainable inventory level is, the lower is the carbon tax cost and the higher is the profit per unit product. Therefore, the retailer increases its sales effort to increase profit. Equation (5) indicates that s_l^* increases monotonically with increase in x. By increasing its sales effort x, a retailer can enhance the sustainable inventory level s_l^*.

Corollary 3. *The retailer's sustainable inventory level s_l and the supplier's sustainable transportation level s_p are positively related under the carbon tax.*

Equation (5) shows that if the supplier increases the sustainable transportation level, then the retailer will increase the sustainable inventory level. Moreover, equation (7) shows that if the retailer increases the sustainable inventory level, then the supplier will increase the sustainable transportation level. Therefore, when considering the carbon tax, the retailer's sustainable inventory investment decisions and the supplier's sustainable transportation investment decisions interact with and promote each other.

Corollary 4. *Under the carbon tax, the retailer's optimal sustainable inventory level is $s_l^* > (p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta)$.*

Equation (5) indicates that when $x = 0$ and $s_p = 0$, the retailer's optimal sustainable inventory level is $s_l = (p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta)$. According to Corollaries 2 and 3, increases in x and s_p can enhance s_l^*. Under the carbon tax, $x > 0$ and $s_p > 0$. Therefore, $s_l^* > (p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta)$.

4.3. Solution for Optimal Sustainable Levels under a Carbon Tax. In the preceding analysis, equations (4), (5), and (7) provide analytical expressions of x^*, s_l^*, and s_p^*, respectively. However, these three decision variables are nested in each other in these three equations, and they cannot be directly obtained from the corresponding formula. An iterative method is required to solve for these three decision variables.

A careful analysis revealed three implicit mathematical results from the previous conclusions:

(1) The retailer's sales profit increases monotonically with the sustainable inventory level s_l

(2) The retailer's profit from sustainable inventory investment increases monotonically for $s_l \in [0, (p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta)]$ and decreases

monotonically for $s_l \in [(p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta), (a_l/b_l)]$

(3) The supplier's profit increases monotonically with the sustainable inventory level s_l

According to the aforementioned information, we can conclude that, in the interval $[(p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta), (a_l/b_l)]$, an optimal sustainable inventory level s_l^* must maximize the expected profits of the retailer and the supplier. Therefore, the following iterative method is introduced to obtain the optimal solutions:

Step 1: let $i = 1$ and $s_l(i) = (p - w_1 - c_l - ra_l)\beta/(\delta_l - 2rb_l\beta)$; initialize $\pi_R(0)$ as zero.

Step 2: calculate $Q(i)$, $x(i)$, and $s_p(i)$ by substituting $s_l(i)$ into equations (2), (4), and (7), respectively.

Step 3: calculate $\pi_R(i)$ by substituting $s_l(i)$, $x(i)$, $s_p(i)$, and $Q(i)$ into equation (1). If $\pi_R(i) \le \pi_R(i-1)$, the procedure terminates, and $s_l(i)$, $x(i)$, and $s_p(i)$ are the optimal values; thus, $s_l^* = s_l(i)$, $x^* = x(i)$, and $s_p^* = s_p(i)$. Otherwise, let $i = i + 1$ and go to Step 4.

Step 4: calculate $s_l(i)$ by substituting $x(i-1)$ and $s_p(i-1)$ into equation (13) and return to Step 2.

5. Multiplayer Dynamic Game Optimization Model

The optimal sustainable levels for transportation and inventory can be determined using the optimization method described in Section 4 given the wholesale price w and carbon tax rate r. However, sustainable transportation and inventory levels are related to carbon tax rates and wholesale prices, which affect retailers' and suppliers' profits. Therefore, appropriate carbon tax rates and wholesale prices are crucial for the coordinated operation of the supply chain. The dynamic game method with complete information was used to construct a three-stage game optimization model to determine the optimal wholesale prices and carbon tax rates. Table 3 displays the basic information of the game, and the optimization processes of each stage of the game simulation are illustrated in Figure 2.

5.1. Wholesale Price Game (Stage 1). In stage 1, the effect of the carbon tax is neglected (i.e., $r = 0$). By substituting $r = 0$ into equations (5) and (7), we can determine the optimal sustainable levels for inventory and transportation (denoted by s_l^{0*} and s_p^{0*}, respectively) as follows:

$$s_l^{0*} = \frac{(p - w - c_l)\beta}{\delta_l}, \qquad s_p^{0*} = \frac{(w - c_s - c_p)\beta}{\delta_p}. \tag{9}$$

We then calculate the retailer's profit and supplier's profit by substituting $r = 0$, s_l^{0*}, and s_p^{0*} into equations (1) and (6).

In the supplier-retailer relationship, the supplier is the dominant party because wholesale prices are set by the supplier. If the retailer accepts this price, both parties trade at this price, and the game is finished. If the retailer does not accept this price, then the supplier gradually reduces the price until the retailer accepts it. When considering the opportunity cost, the equilibrium condition for a retailer is that its profit rate is higher than the social average. Otherwise, the retailer would choose another investment opportunity. When a retailer's profit rate is higher than the social average, the supplier will not reduce the wholesale price because it can easily find other retailers in the market. Therefore, retailers no longer require suppliers to reduce wholesale prices, and the Nash equilibrium is achieved.

5.2. Carbon Tax Rate Game (Stage 2). The dominant party in stage 2 is the government, the goal of which is to maximize social welfare. Social welfare is expressed in equation (10). The first term in equation (10) is economic utility, and the second term is environmental utility. Economic utility is a positive utility that is determined using equation (11). In equation (11), the first term is the supplier's profit, the second term is the retailer's profit, and the third term is the carbon tax revenue. Environmental utility is a disutility and reflects the environmental damage caused by carbon emissions. A quadratic environmental damage function [54] is used to represent the environmental utility, as illustrated in equation (12).

$$SW = U_{\text{ec}} - U_{\text{en}}, \tag{10}$$

$$U_{\text{ec}} = \pi_R + \pi_V + r\left(a_l + a_p - b_l s_l - b_p s_p\right)Q, \tag{11}$$

$$U_{\text{en}} = \frac{\theta\left(a_l + a_p - b_l s_l - b_p s_p\right)^2 Q^2}{2}. \tag{12}$$

Stage 2 involves three players. Based on the Stackelberg game, a government sets a carbon tax rate, and suppliers and retailers select sustainable levels of transportation and inventory by using the optimization model presented in Section 4. If profits are lower than expected, suppliers and retailers will abandon the investments, which will result in no social welfare. In the simulation game, the government gradually reduces the carbon tax rate from a high level until it is accepted by suppliers and retailers. The game equilibrium maximizes social welfare while suppliers and retailers achieve their expected profit rates.

5.3. Sustainable Investment-Sharing Strategy Game (Stage 3). Carbon tax policy imposes a negative financial burden on companies [17]. To encourage enterprises to strengthen their efforts to reduce carbon emissions, a government can implement a sustainable investment-sharing strategy. The sharing proportions of the government and enterprises are k and $1 - k$, respectively. In this strategy, government

Table 3: Basic game information.

Stage	Players			Optimization objective
	Government	Supplier	Retailer	
1		✓	✓	Wholesale price
2	✓	✓	✓	Carbon tax rate
3	✓	✓	✓	Sustainable investment-sharing proportion

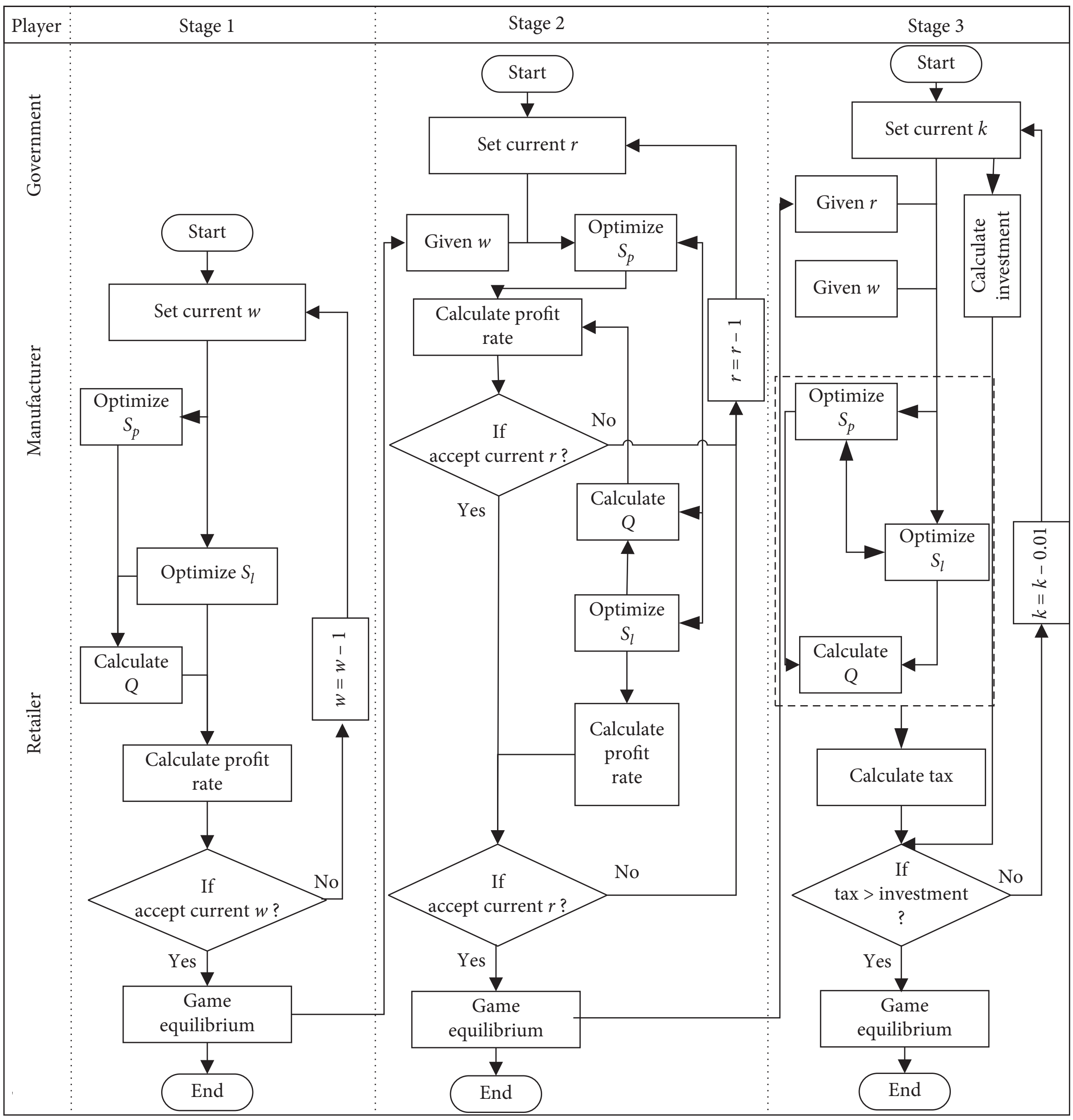

Figure 2: Three-stage game simulation of optimization process.

sustainable investment is represented as $k(\delta_l s_l^2 + \delta_p s_p^2)/2$, and sustainable investments of suppliers and retailers are $(1-k)\delta_l s_l^2/2$ and $(1-k)\delta_p s_p^2/2$, respectively. The expected profit functions of retailers and suppliers are as follows:

$$\begin{aligned}\pi_R^I &= E\left[p\min(Q,D) - (w + c_l)Q - g(x) - \frac{(1-k)\delta_l s_l^2}{2} + v(Q-D)^+ - r(a_l - b_l s_l)Q\right],\\ \pi_V^I &= \left(w - c_s - c_p - r\left(a_p - b_p s_p\right)\right)Q - \frac{(1-k)\delta_p s_p^2}{2}.\end{aligned} \tag{13}$$

By using the same derivation as in Section 4, we can obtain the optimal sustainable levels of inventory and transportation as follows:

$$s_l^{I\,*} = \frac{(p - w - c_l - ra_l)\beta + rb_l\left(f(x^{II}) + \beta s_p\right)}{(1-k)\delta_l - 2rb_l\beta}, \tag{14}$$

$$s_p^{I\,*} = \frac{\left(w - c_s - c_p - ra_p\right)\beta + rb_p\left(f(x^{II}) + \beta s_l^{II} + F^{-1}\left(p - w - c_l - r\left(a_l - b_l s_l^{II}\right)/(p - v)\right)\right)}{(1-k)\delta_p - 2rb_p\beta}. \tag{15}$$

Equations (14) and (15) indicate that the optimal sustainable levels of inventory and transportation increase monotonically with the sharing proportion of government k.

The sustainable investment-sharing strategy is optimized based on the Stackelberg game between the government and the enterprises (i.e., suppliers and retailers). Suppliers and retailers will accept any government strategy. However, higher proportions of government investment induce higher sustainable levels of transportation and inventory, which improve social welfare but reduce carbon tax revenue. Therefore, a balance between social welfare, investment, and carbon tax revenue is required. However, the primary aim of the carbon tax policy is to improve the environment rather than raise revenue. This model assumes that governments aim to maximize social welfare when carbon tax revenue is higher than the investment. In this game, the government first sets the investment-sharing proportion to a relatively high value and then gradually reduces it. When the government achieves the decision objectives, the game reaches its Nash equilibrium.

6. Simulation Analysis and Results

6.1. Simulation Method and Accuracy Analysis. To illustrate the simulation method for game optimization and analyze the effect of a carbon tax on supply chain performance, supply chains were studied in specific situations. In the following numerical examples, let $\xi \sim N(200, 20)$, $p = 80\,\text{CNY}$, $C_s = 25\,\text{CNY}$, $C_l = 2\,\text{CNY}$, $C_p = 3\,\text{CNY}$, $v = 5\,\text{CNY}$, $a_p = 50\,\text{kg}$, $b_p = 5\,\text{kg}$, $a_l = 30\,\text{kg}$, $b_l = 3\,\text{kg}$, $\beta = 140$, $\delta_p = 1500\,\text{CNY}$, $\delta_l = 1200\,\text{CNY}$, and $\theta = 3\,\text{CNY}$. Given that $f'(x) > 0$, $f''(x) < 0$, $g'(x) > 0$, and $g''(x) \geq 0$, we set $f(x) = 10x^{1/2}$ and $g(x) = x$ [55]. The expression $f(x) = 10x^{1/2}$ shows that the regularity of demand generated by sales effort varies with sales effort, and $g(x) = x$ indicates that when the retailer increases sales effort by one unit, the cost incurred for sales effort is 1 CNY. The constant operating costs of the supplier and the retailer were set at $20,000\,\text{CNY}$ and $15,000\,\text{CNY}$, respectively.

The simulation calculations for each stage of the three-stage game optimization process were programmed separately in MATLAB (Figure 2). A total of 500 simulation cycles were implemented. The relative error ε of the simulation result was calculated using equation (16), where X and σ are the mean and standard deviation, respectively, of 500 simulation results. The simulation accuracy was set to 99%, and the allowable relative error was set to 5%. Social welfare was selected as the test index, and statistical analyses of the simulation results are illustrated in Table 4. According to Table 4, the relative errors of the results for the 500 simulations were all <5%. The accuracy of the simulation results satisfied research requirements, and these results were used for decision analysis.

$$\varepsilon = \frac{t_{499,0.99}\sqrt{\sigma^2/500}}{X(500)}. \tag{16}$$

6.2. Simulation Results and Optimal Decisions

6.2.1. Simulation Results of the Wholesale Price Game (Stage 1). Let $r = 0$, and suppose that the average social profit rate for the product is 15%. Set $w = 30, 31, \ldots, 65\,\text{CNY}$, and simulate the supply chain operations for each of the 36 wholesale price situations. Table 5 summarizes the results of stage 1. When $w = 49\,\text{CNY}$, retailer profit was 15.34%. When $w > 49\,\text{CNY}$, retailer profit was <15%. Therefore, the maximum acceptable wholesale price for retailers was 49 CNY. The relationship between the supplier and the retailer indicated that the optimal wholesale price determined by the supplier was 49 CNY.

6.2.2. Simulation Results of the Carbon Tax Rate Game (Stage 2). Let $w = 49\,\text{CNY}$, and suppose that the average social profit rate for the product is 10% after the implementation of the carbon tax. Simulation experiments revealed that the sustainable transportation and inventory levels were maximized when $r = 623\,\text{CNY/ton}$. For $r > 623\,\text{CNY/ton}$, increases in the carbon tax rate had no effect on the operation of the supply chain. Therefore, we investigated tax rates in the range of 1–623 CNY/ton and simulated the supply chain operations for each of the 623 carbon tax rates. Table 6 summarizes the results of stage 2.

According to the simulation results, social welfare exhibits an inverted U-shaped trend with increases in the carbon tax rate. When $r = 529\,\text{CNY/ton}$, social welfare was maximized at a value of 51,276 CNY. However, the profits of the supplier and the retailer were −6.86% and 9.02%, respectively. If the government sets the tax rate at 529CNY/ton, both suppliers and retailers abandon their

Table 4: Accuracy of the simulation results.

Game stage	Mean (CNY)	Standard deviation	Half-interval	Relative error (%)
Stage 1	7944	2924.6	336.79	4.24
Stage 2	23,462	1802.2	328.15	1.40
Stage 3	31,455	1681.6	306.18	0.97

Table 5: Decision information for the wholesale price game (stage 1).

Indicators	Wholesale price w (CNY)				
	30~47 (%)	48 (%)	49 (%)	50 (%)	51~63 (%)
Retailer's profit rate	35.25~17.34	16.34	15.34	14.34	13.33~0.98

businesses because profits do not satisfy expectations. Therefore, after considering the effect on the supplier and the retailer, social welfare was 0. Therefore, tax rates must be reduced to ensure that the supplier and the retailer achieve their expected profit rates. When the carbon tax rate was reduced to 163 CNY/ton, both supplier and retailer achieved their expected profits. Thus, the carbon tax rate game reached equilibrium with an optimal carbon tax rate of 163 CNY/ton.

Under a carbon tax, the supplier bears more costs for sustainable investment and the carbon tax than the retailer does, resulting in a considerable decrease in the supplier's profit. Hence, the supplier attempts to increase the wholesale price w to shift some costs to retailers. We set $r = 163$ CNY/ton; consider $w = 30, 31, \ldots, 65$ CNY; and simulate the supply chain operations for each of the 36 wholesale prices. The results are summarized in Table 7. When $w = 51$ CNY, the retailer's profit was 10.45%. For $w \geq 52$ CNY, the retailer's profit was <10%. Therefore, the supplier could adjust the wholesale price w to 51 CNY.

6.2.3. Simulation Results of the Sustainable Investment-Sharing Strategy Game (Stage 3). Let $w = 51$ CNY and $r = 163$ CNY/ton. Through simulation experiments, we determined that the sustainable transportation and inventory levels reached their maximum when the government's sharing proportion was $k = 57\%$. At this value, further increases in the shared proportion did not improve social welfare; therefore, the shared proportion set by the government should not exceed 57%. With $k = 1\%, 2\%, \ldots, 57\%$, we simulated supply chain operations for each of the 57 investment-sharing strategies. Table 8 summarizes the results of stage 3.

The simulation results indicated that carbon tax revenue decreased with an increase in the shared proportion, whereas government investment increased with an increase in the shared proportion. With $k = 44\%$, social welfare was maximized. For this value, the carbon tax revenue was 12,850 CNY, and the government investment was 31,636 CNY. Therefore, the government was required to invest additional 18,786 CNY. For $k < 44\%$, social welfare increased with the shared proportion. For $k > 44\%$, social welfare decreased with the shared proportion. For $k < 57\%$, tax revenues decreased, and the government investment increased with an increasing shared proportion. For $k = 35\%$, tax revenue was higher than government investment. Therefore, the optimal shared proportion was 35%.

6.3. Summary and Comparison of Optimal Results. The optimal results of each stage are summarized in Table 9. Comparing the results of stages 1 and 2 revealed that the effects of the carbon tax on the supply chain were principally manifested in the following four aspects:

(1) The sustainable transportation level increased by 44.90%, from 1.96 to 2.84, and the sustainable inventory level increased by 7.36%, from 3.38 to 3.64.

(2) Social welfare increased by 24.93%, from 21,664 CNY to 27,254 CNY. Environmental utility decreased by 25.80%, from 30,733 CNY to 26,061 CNY. Economic utility increased by 3.23%, from 52,397 CNY to 50,703 CNY.

(3) Supplier and retailer profits decreased by 51.92% and 31.57%, respectively. The profit structure in the supply chain changed substantially. Without the carbon tax, supplier and retailer profits were 51.87% and 48.13%, respectively. After adopting the carbon tax, supplier and retailer profits were 43.09% and 56.91%, respectively.

(4) The carbon tax revenue increased to 20,380 CNY.

These results demonstrated that the carbon tax improved the sustainable transportation and inventory levels and reduced carbon emissions in logistics, thus reducing environmental utility. When the supplier and the retailer improve their sustainability levels, their sustainable investments are increased correspondingly. However, the increase in sustainable investment does not result in an increase in profits. By contrast, supplier and retailer profits decreased after the introduction of the carbon tax. The conflict between investment and profit reflected the negative effect of the carbon tax on the supplier and the retailer. The increase in the sustainable transportation level after the introduction of the carbon tax was higher than that of the sustainable inventory level, encouraging sustainable investment by the supplier. Moreover, the carbon tax revenue from the supplier was higher than that from the retailer because emissions from transportation are higher than those from inventory. Therefore, the reduction in the supplier's profits was higher than that of the retailer's profits, which adjusted the profit structure in the supply chain. Although the carbon tax had a negative effect on profit in the supply chain, the economic utility of the supply chain did not

Table 6: Decision information for the carbon tax rate game (stage 2).

Indicators	Carbon tax rate r (CNY/ton)					
	1	2~162	163	164~528	529	530~623
Social welfare (CNY)	21,767	21,803~27,034	27,065	27,096~41,274	41,276	36,294~29,811
Supplier's profit rate (%)	30.17	30.01~10.19	10.09	9.99~−6.89	−6.86	−6.82~-0.89
Retailer's profit rate (%)	15.36	15.33~12.13	12.11	12.09~9.00	9.02	9.03~9.83

Table 7: Wholesale price adjustment in stage 2.

Indicators	Wholesale price w (CNY)				
	30~49 (%)	50 (%)	51 (%)	52 (%)	53~63 (%)
Retailer's profit rate	34.13~12.12	11.54	10.45	9.37	8.28~−10.48

Table 8: Decision information for the sustainable investment-sharing strategy game (stage 3).

Indicators (CNY)	Government's sharing proportion k					
	1%	2%~34%	35%	36%~43%	44%	45%~57%
Social welfare	26,491	26,275~39,121	39,588	40,046~42,395	42,460	43,395~27,248
Tax revenue	20,372	20,363~17,499	17,210	16,892~13,551	12,850	12,069~0
Government's investments	153.8	295.13~15,875	15,875	17,101~29,210	31,636	34,302~76,950

Table 9: Summary of optimal results.

Indicators	Stage 1	Stage 2	Stage 3
Transportation sustainable level	1.96	2.84	6.34
Inventory sustainable level	3.38	3.64	5.32
Supplier's profit (CNY)	27,176	13,065	25,132
Retailer's profit (CNY)	25,221	17,258	29,842
Profit of the whole supply chain (CNY)	52,397	30,323	54,974
Supplier's profit rate (%)	30.32	12.67	19.11
Retailer's profit rate (%)	15.34	10.45	13.89
Economical utility (CNY)	52,397	50,703	56,309
Environmental utility (CNY)	30,733	23,449	16,721
Social welfare (CNY)	21,664	27,254	39,588
Tax revenues (CNY)	0	20,380	17,210
Government's investments (CNY)	0	0	15,875

decrease because the government received carbon tax revenue. However, with the rapid decline in the environmental utility, the social welfare of the entire supply chain was significantly improved. Therefore, although the carbon tax had negative effects on enterprises [17], it induced positive effects for the society.

The optimization results of stages 2 and 3 indicated that the effects of sustainable investment-sharing strategies on the supply chain were as follows:

(1) The sustainable transportation and inventory levels increased by 123.24% and 46.15%, respectively.

(2) Social welfare increased by 45.26% to 39,588 CNY, and economic utility increased by 11.06% to 56,309 CNY, whereas environmental utility decreased by 28.69% to 16,721 CNY.

(3) Supplier and retailer profits increased by 92.36% and 72.92%, respectively. The proportions of supplier and retailer profits were 45.72% and 54.28%, respectively. The profit structure in the supply chain trended towards a balance.

(4) The carbon tax revenue decreased to 17,210 CNY. The sustainable investment of the government was 15,875 CNY, and the actual revenue (i.e., tax revenue minus investment) was 1,335 CNY.

The sustainable investment-sharing strategy improved supply chain performance for the government and enterprises. It reduced the marginal investment cost for the supplier and the retailer, thus providing an incentive to improve sustainability. A higher government share proportion induced more sustainable practices. By sharing the investment cost with the government, the supplier and the retailer obtained more revenue at a reduced cost. With the improvement in sustainability, the supplier and the retailer reduced their carbon emissions in logistics, thereby reducing the environmental utility and their carbon tax costs. The reduction in carbon tax costs increased the profits of enterprises, thereby increasing their economic utility. The dual function of economic utility and environmental utility resulted in a rapid increase in social welfare. Notably, the sustainable investment-sharing strategy had a more substantial effect on the supplier because suppliers generate higher carbon emissions than retailers do.

Compared with the results of stage 1, the optimization strategy of stage 3 increased the government revenues (1,335 CNY), social welfare (39,588 CNY), and the profit of the entire supply chain (54,974 CNY), thus coordinating the interests of the government and enterprises. These results indicated that the sustainable investment-sharing strategy not only promoted the positive role of the carbon tax for the sustainable logistics level, social welfare, and environmental utility but also effectively compensated for the negative effect of the carbon tax on enterprise profits. Therefore, the

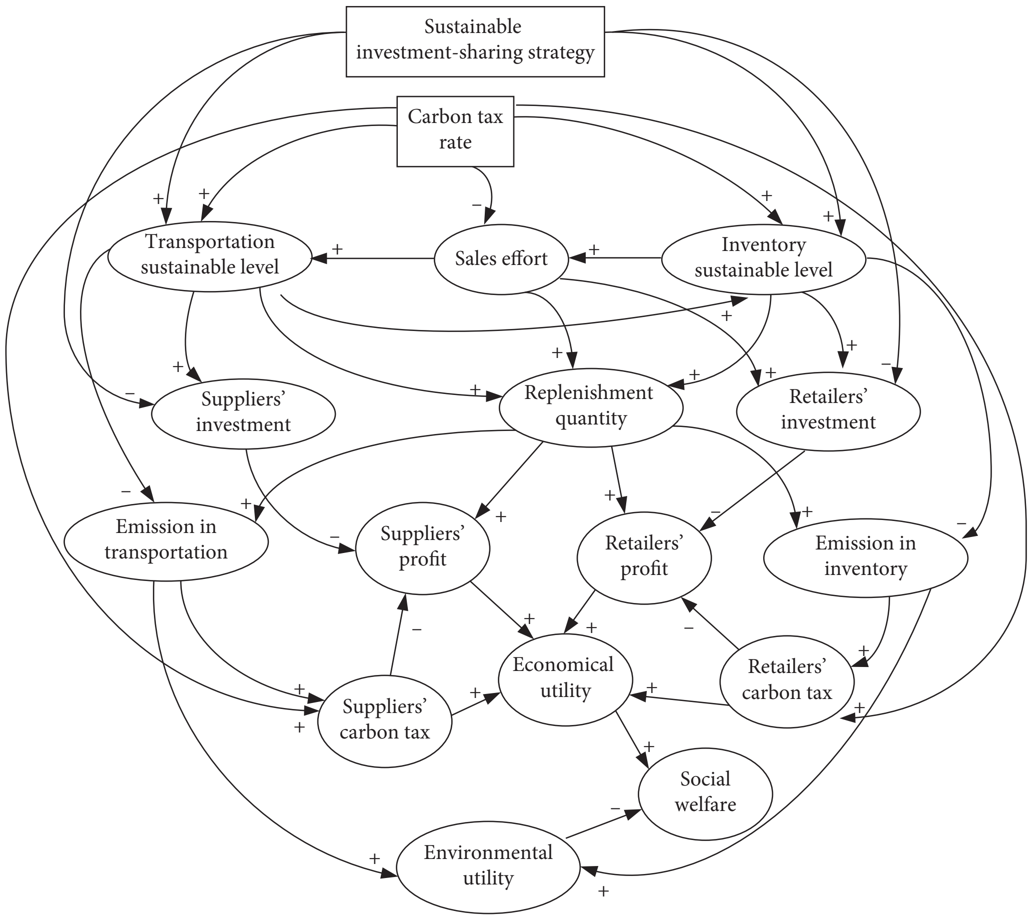

Figure 3: Causal relationships of the sustainable transportation and inventory system.

proposed combined optimization of the carbon tax and the sustainable investment-sharing strategy can increase social welfare, stimulate enthusiasm for carbon emission reduction in enterprise logistics, and facilitate supply chain coordination.

6.4. Implications for Management. Figure 3 shows the mechanisms and effects of the carbon tax and the sustainable investment-sharing strategy as well as the internal relationships between the supply chain elements.

The decisions of suppliers and retailers regarding sustainable investment are interlinked. To ensure that enterprises can make optimal investments in transportation and inventory to reduce carbon emissions, both suppliers and retailers must establish communication mechanisms to reach consensus and reduce carbon emissions [46]. Suppliers' sustainable investments in inventory benefit retailers, and retailers' sustainable investment and sales investment benefit suppliers. Suppliers and retailers should use the benefits of supply chain spillovers to reasonably share investment costs and encourage the other parties to enhance their sustainable investment [6, 45]. Therefore, incentive mechanisms should be implemented to reduce carbon emissions by suppliers and retailers. When formulating policies, governments should compromise between social welfare and corporate goals. High carbon taxes can harm government revenues and enterprises. When implementing a sustainable investment-sharing strategy, the government should prioritize enterprises with high carbon emissions to maximize the effect of emission reduction. When financial expenditure is sufficient or the task of reducing carbon emissions is challenging, governments can increase their share of sustainable investment to reduce environmental utility and improve social welfare.

7. Conclusions

7.1. Discussion. Sustainable supply chain management is a widely discussed topic in environmental sustainability, and a carbon tax is an effective method for reducing carbon emissions. Transportation and inventory management are the two core factors that affect economic and environmental utilities in logistics. However, research on joint decision-making for sustainable transportation and inventory management when a carbon tax is implemented on a global scale is lacking. We investigated a two-part supply chain in which the supplier first determines the sustainable transportation level and the retailer then places an order and assesses the sustainable inventory level relative to sales effort. We integrated the optimization of sustainable transportation and inventory levels and identified an approach to improve sustainable supply chain performance when a carbon tax is implemented and the government shares sustainable investment with enterprises.

For suppliers and retailers, they must maintain appropriate sustainable transportation and inventory levels under a carbon tax. We adopted a Stackelberg game to optimize the sustainable transportation and inventory levels. Because the three factors, namely, sales effort, inventory sustainability, and transportation sustainability, influenced each other in the decision-making process, optimal results could not be directly deduced, and thus, an iterative process was designed to solve the optimization problem. The results revealed that the carbon tax policy encouraged suppliers and retailers to increase their sustainable transportation and inventory levels [25], thus reducing carbon emissions in the logistics industry. Increasing the sustainable inventory level improved retailers' sales efforts. However, an increase in carbon tax costs reduced sales motivation.

For the government, the carbon tax rate must be set to improve environmental utility and social welfare. To solve this problem, we developed a three-stage dynamic game optimization model. The wholesale price was determined in the first stage, which included suppliers and retailers. In the second stage, which also included the government, the carbon tax rate was optimized, and the wholesale price was adjusted accordingly. The sustainable investment-sharing strategy was considered in the third stage. We implemented a MATLAB simulation to solve this three-stage game model.

A single carbon tax has a dual effect on the performance of the supply chain, and an appropriate sustainable investment-sharing strategy can harmonize government and enterprise objectives. The results of numerical studies indicated that the carbon tax played a strong role in improving environmental utility and social welfare. However, such a policy hinders enterprises [43]. Enterprises increased their sustainable investments, but their profits decreased. The sustainable investment-sharing strategy can stimulate enterprises to promote sustainability, reduce environmental utility, and increase social welfare. This may enable an increase in profits for enterprises with less investment, which would offset the negative effect of the carbon tax on enterprises. An appropriate sustainable investment-sharing strategy can promote the interests of governments and enterprises and improve sustainability in the supply chain.

The novel contributions of this paper are summarized as follows. An integrated optimization model for sustainable transportation and inventory management was developed. To the best of our knowledge, this study is the first to combine two sustainable logistics factors in the supply chain. Furthermore, a three-stage dynamic game model was proposed to optimize wholesale prices, carbon tax rates, and investment-sharing strategies. The proposed model could be used as a framework for governments that intend to implement a carbon tax and enterprises that are committed to developing sustainable logistics.

7.2. Limitations and Future Research. Although this paper makes several novel contributions, certain limitations should be noted, and future studies should address the following: (1) the carbon tax rate was set as a fixed value in the model. Uncertain carbon tax rates should be discussed in future studies. (2) Our study only considered the carbon tax. However, sustainable investment under other carbon emission-reduction policies, such as carbon cap, carbon cap-and-trade, and carbon offset, also warrants further study. (3) The supply chain network structure has certain limitations. Future research should investigate more complex supply chain networks such as one-to-many, many-to-one, and many-to-many. Routing problems in these networks complicate the optimization process. In such networks, the measurement of sustainable transportation levels in different routing schedules and the differences in consumer environmental awareness in different markets would increase the value and challenge of the problem. (4) The spillover effect of sustainable investment has a major influence on decision-making in supply chain enterprises. Future studies should focus on the spillover effect in one-to-many, many-to-one, and many-to-many supply chains. We should further analyze the horizontal and vertical benefit spillovers and the coordination mechanisms within these supply chains.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] F. Testa, F. Iraldo, and M. Frey, "The effect of environmental regulation on firms' competitive performance: the case of the building & construction sector in some EU regions," *Journal of Environmental Management*, vol. 92, no. 9, pp. 2136–2144, 2011.

[2] Z. Xu, A. Elomri, S. Pokharel, and F. Mutlu, "The design of green supply chains under carbon policies: a literature review of quantitative models," *Sustainability*, vol. 11, no. 11, p. 3094, 2019.

[3] A. Chelly, I. Nouira, Y. Frein, and A. B. Hadj-Alouane, "On the consideration of carbon emissions in modelling-based supply chain literature: the state of the art, relevant features and research gaps," *International Journal of Production Research*, vol. 57, no. 15-16, pp. 4977–5004, 2019.

[4] B. Fahimnia, J. Sarkis, A. Choudhary, and A. Eshragh, "Tactical supply chain planning under a carbon tax policy scheme: a case study," *International Journal of Production Economics*, vol. 164, pp. 206–215, 2015.

[5] G. J. L. Micheli and F. Mantella, "Modelling an environmentally-extended inventory routing problem with demand uncertainty and a heterogeneous fleet under carbon control policies," *International Journal of Production Economics*, vol. 204, pp. 316–327, 2018.
[6] C. Dong, B. Shen, P.-S. Chow, L. Yang, and C. T. Ng, "Sustainability investment under cap-and-trade regulation," *Annals of Operations Research*, vol. 240, no. 2, pp. 509–531, 2016.
[7] P. Rao and D. Holt, "Do green supply chains lead to competitiveness and economic performance?" *International Journal of Operations & Production Management*, vol. 25, no. 9, pp. 898–916, 2005.
[8] Y. Cheng, Y. Kuang, X. Shi, and C. Dong, "Sustainable investment in a supply chain in the big data era: an information updating approach," *Sustainability*, vol. 10, no. 2, p. 403, 2018.
[9] Y. Bouchery, A. Ghaffari, Z. Jemai, and Y. Dallery, "Including sustainability criteria into inventory models," *European Journal of Operational Research*, vol. 222, no. 2, pp. 229–240, 2012.
[10] T. Rebs, M. Brandenburg, and S. Seuring, "System dynamics modeling for sustainable supply chain management: a literature review and systems thinking approach," *Journal of Cleaner Production*, vol. 208, pp. 1265–1280, 2019.
[11] S. A. R. Khan, "Green supply chain management, economic growth and environment: a GMM based evidence," *Journal of Cleaner Production*, vol. 185, pp. 588–599, 2018.
[12] D. Konur and B. Schaefer, "Integrated inventory control and transportation decisions under carbon emissions regulations: LTL vs. TL carriers," *Transportation Research Part E: Logistics and Transportation Review*, vol. 68, pp. 14–38, 2014.
[13] S. A. R. Khan and D. Qianli, "Does national scale economic and environmental indicators spur logistics performance? Evidence from UK," *Environmental Science and Pollution Research*, vol. 24, no. 34, pp. 26692–26705, 2017.
[14] Q. Zhu, J. Sarkis, and K.-h. Lai, "Initiatives and outcomes of green supply chain management implementation by Chinese manufacturers," *Journal of Environmental Management*, vol. 85, no. 1, pp. 179–189, 2007.
[15] R. Dekker, J. Bloemhof, and I. Mallidis, "Operations Research for green logistics - an overview of aspects, issues, contributions and challenges," *European Journal of Operational Research*, vol. 219, no. 3, pp. 671–679, 2012.
[16] W. W. Qu, J. H. Bookbinder, and P. Iyogun, "An integrated inventory-transportation system with modified periodic policy for multiple products," *European Journal of Operational Research*, vol. 115, no. 2, pp. 254–269, 1999.
[17] T. Shu, C. Huang, S. Chen, S. Wang, and K. K. Lai, "Trade-old-for-remanufactured closed-loop supply chains with carbon tax and government subsidies," *Sustainability*, vol. 10, no. 11, p. 3935, 2018.
[18] Z.-Y. Chen and P.-Y. Nie, "Effects of carbon tax on social welfare: a case study of China," *Applied Energy*, vol. 183, pp. 1607–1615, 2016.
[19] D. J. Olsen, Y. Dvorkin, R. Fernandez-Blanco, and M. A. Ortega-Vazquez, "Optimal carbon taxes for emissions targets in the electricity sector," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 5892–5901, 2018.
[20] X. Ma, W. Ho, P. Ji, and S. Talluri, "Coordinated pricing analysis with the carbon tax scheme in a supply chain," *Decision Sciences*, vol. 49, no. 5, pp. 863–900, 2018.
[21] J. Xie, H. Dai, Y. Xie, and L. Hong, "Effect of carbon tax on the industrial competitiveness of Chongqing, China," *Energy for Sustainable Development*, vol. 47, pp. 114–123, 2018.
[22] X.-Y. Bao and L. Zhang, "Green procurement relationships development under carbon emissions regulations: a bi-level programming approach," *International Journal of Environmental Research and Public Health*, vol. 15, no. 10, p. 2183, 2018.
[23] X. Xin, X. Wang, X. Tian, Z. Chen, and K. Chen, "Green scheduling model of shuttle tanker fleet considering carbon tax and variable speed factor," *Journal of Cleaner Production*, vol. 234, pp. 1134–1143, 2019.
[24] C. Wang, W. Wang, and R. Huang, "Supply chain enterprise operations and government carbon tax decisions considering carbon emissions," *Journal of Cleaner Production*, vol. 152, pp. 271–280, 2017.
[25] L. Wang, T. Xu, and L. Qin, "A study on supply chain emission reduction level based on carbon tax and consumers' low-carbon preferences under stochastic demand," *Mathematical Problems in Engineering*, vol. 2019, Article ID 1621395, 20 pages, 2019.
[26] S. Ding, M. Zhang, and Y. Song, "Exploring China's carbon emissions peak for different carbon tax scenarios," *Energy Policy*, vol. 129, pp. 1245–1252, 2019.
[27] M. Alizadeh, J. Ma, M. Marufuzzaman, and F. Yu, "Sustainable olefin supply chain network design under seasonal feedstock supplies and uncertain carbon tax rate," *Journal of Cleaner Production*, vol. 222, pp. 280–299, 2019.
[28] P. Gautam and A. Khanna, "An imperfect production inventory model with setup cost reduction and carbon emission for an integrated supply chain," *Uncertain Supply Chain Management*, vol. 6, no. 3, pp. 271–286, 2018.
[29] V. Gaur and M. L. Fisher, "A periodic inventory routing problem at a supermarket chain," *Operations Research*, vol. 52, no. 6, pp. 813–822, 2004.
[30] H. Andersson, A. Hoff, M. Christiansen, G. Hasle, and A. Løkketangen, "Industrial aspects and literature survey: combined inventory management and routing," *Computers & Operations Research*, vol. 37, no. 9, pp. 1515–1536, 2010.
[31] M. Bonney and M. Y. Jaber, "Environmentally responsible inventory models: non-classical models for a non-classical era," *International Journal of Production Economics*, vol. 133, no. 1, pp. 43–53, 2011.
[32] S. Tang, W. Wang, S. Cho, and H. Yan, "Reducing emissions in transportation and inventory management: (R, Q) Policy with considerations of carbon reduction," *European Journal of Operational Research*, vol. 269, no. 1, pp. 327–340, 2018.
[33] V. Hovelaque and L. Bironneau, "The carbon-constrained EOQ model with carbon emission dependent demand," *International Journal of Production Economics*, vol. 164, pp. 285–291, 2015.
[34] G. Hua, T. C. E. Cheng, and S. Wang, "Managing carbon footprints in inventory management," *International Journal of Production Economics*, vol. 132, no. 2, pp. 178–185, 2011.
[35] X. Chen, S. Benjaafar, and A. Elomri, "The carbon-constrained EOQ," *Operations Research Letters*, vol. 41, no. 2, pp. 172–179, 2013.
[36] P. Gautam, A. Kishore, A. Khanna, and C. K. Jaggi, "Strategic defect management for a sustainable green supply chain," *Journal of Cleaner Production*, vol. 233, pp. 226–241, 2019.
[37] S. Wang, F. Tao, and Y. Shi, "Optimization of inventory routing problem in refined oil logistics with the perspective of carbon tax," *Energies*, vol. 11, no. 6, p. 1437, 2018.
[38] K. Nageswara Reddy, A. Kumar, J. Sarkis, and M. K. Tiwari, "Effect of carbon tax on reverse logistics network design," *Computers and Industrial Engineering*, vol. 139, Article ID 106184, 2020.

[39] D. F. Drake and S. Spinler, “OM forum-sustainable operations management: an enduring stream or a passing fancy?” *Manufacturing & Service Operations Management*, vol. 15, no. 4, pp. 689–700, 2013.

[40] X. Shi, Y. Qian, and C. Dong, “Economic and environmental performance of fashion supply chain: the joint effect of power structure and sustainable investment,” *Sustainability*, vol. 9, no. 6, p. 961, 2017.

[41] C. Su, X. Liu, and W. Du, “Green supply chain decisions considering consumers’ low-carbon awareness under different government subsidies,” *Sustainability*, vol. 12, no. 6, p. 2281, 2020.

[42] S. Benjaafar, Y. Li, and M. Daskin, “Carbon footprint and the management of supply chains: insights from simple models,” *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 1, pp. 99–116, 2012.

[43] D. Krass, T. Nedorezov, and A. Ovchinnikov, “Environmental taxes and the choice of green technology,” *Production and Operations Management*, vol. 22, no. 5, pp. 1035–1055, 2013.

[44] J. Chen, “Green technology choice under environmental taxes,” in *Proceedings of the 2015 12th International Conference on Service Systems and Service Management (ICSSSM)*, IEEE, Guangzhou, China, June 2015.

[45] D. F. Drake, P. R. Kleindorfer, and L. N. Van Wassenhove, “Technology choice and capacity portfolios under emissions regulation,” *Production and Operations Management*, vol. 25, no. 6, pp. 1006–1025, 2016.

[46] A. Toptal, H. Özlü, and D. Konur, “Joint decisions on inventory replenishment and emission reduction investment under different emission regulations,” *International Journal of Production Research*, vol. 52, no. 1, pp. 243–269, 2014.

[47] C.-T. Zhang and L.-P. Liu, “Research on coordination mechanism in three-level green supply chain under noncooperative game,” *Applied Mathematical Modelling*, vol. 37, no. 5, pp. 3369–3379, 2013.

[48] S. Du, J. Zhu, H. Jiao, and W. Ye, “Game-theoretical analysis for supply chain with consumer preference to low carbon,” *International Journal of Production Research*, vol. 53, no. 12, pp. 3753–3768, 2015.

[49] Z. Liu, T. D. Anderson, and J. M. Cruz, “Consumer environmental awareness and competition in two-stage supply chains,” *European Journal of Operational Research*, vol. 218, no. 3, pp. 602–613, 2012.

[50] Y. Yu, X. Han, and G. Hu, “Optimal production for manufacturers considering consumer environmental awareness and green subsidies,” *International Journal of Production Economics*, vol. 182, pp. 397–408, 2016.

[51] I. R. Webb and R. C. Larson, “Period and phase of customer replenishment: a new approach to the strategic inventory/routing problem,” *European Journal of Operational Research*, vol. 85, no. 1, pp. 132–148, 1995.

[52] X. Pu, L. Gong, and X. Han, “Consumer free riding: coordinating sales effort in a dual-channel supply chain,” *Electronic Commerce Research and Applications*, vol. 22, pp. 1–12, 2017.

[53] S. Swami and J. Shah, “Channel coordination in green supply chain management,” *Journal of the Operational Research Society*, vol. 64, no. 3, pp. 336–351, 2013.

[54] T. A. Weber and K. Neuhoff, “Carbon markets and technological innovation,” *Journal of Environmental Economics and Management*, vol. 60, no. 2, pp. 115–132, 2010.

[55] T. Hongxiang, “Analysis on influence of VMI on the performance of supply chain,” *Chinese Journal of Management Science*, vol. 12, no. 2, p. 6, 2004.