Recycling model of low-carbon and closed-loop supply chain considering government subsidies

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Abstract
To find the manufacturer’s optimal recycling mode under the dual factors of government subsidies and consumers’ low-carbon preference, we construct three game models by taking the wholesale price, retail price, recovery rate, and carbon emission reduction level as the decision variables. Then, Stackelberg Game and Mathematica 12.0 are used to work out the equilibrium strategies of the recovery model, then we reveal the impact of government subsidies and consumers’ low-carbon preference on the closed-loop supply chain. (1) Entrusting retailers to recycle is the best choice. (2) The government subsidy to the manufacturer and retailer within a certain range is conducive to promoting recycling activities and has a positive impact on the manufacturer’s cost savings and carbon emission reduction investment. Nevertheless, the effect of subsidizing the third party is not obvious. (3) Cultivating consumers’ low-carbon preference for low-carbon/remanufactured products can not only directly promote the overall profit of the closed-loop supply chain, but also increase the rate of recovery and level of carbon emission reduction. Thus, the government should increase the subsidized prices of manufacturers and retailers and there is no need to subsidize third parties. It is necessary to cultivate consumers’ low-carbon preference, which is conducive to promoting manufacturers’ carbon emission reduction activities.

KEYWORDS
closed-loop supply chain, consumers’ low-carbon preference, government subsidies, recycling model

1 | INTRODUCTION

Countries around the world strive to seek a balance between economic and environmental benefits, and sustainable development is an inevitable trend in the future.\(^1\) Research and practices have proved that the collection and remanufacturing of waste products is one of the effective ways to reduce carbon emissions and environmental pollution,\(^2\)\(^–\)\(^4\) which can reduce manufacturing costs by up to 40%–65%.\(^5\)\(^,\)\(^6\) For instance, Fuji Xerox has established a complete recycling system, continuously increasing the recycling rate of products, and
reducing production costs by more than 40%. Volkswagen has saved 70% of its costs by using recycled car engines and other components. Therefore, the “Closed-Loop Supply Chain (CLSC)” with both environmental and economic benefits has attracted widespread attention from the government, enterprises, and academia.7,8

CLSC consists of two parts: the traditional forward supply chain and the reverse logistics, including product recycling, which pursues a closed-loop feedback cycle process of “resource-production-consumption-renewable resources.”9–11 Manufacturing enterprises intend to implement remanufacturing by constructing an efficient CLSC, aiming to reduce costs and establish a social image to form a strong competitiveness.12,13 There are many recycling modes available for enterprises to choose from. For example, Canon directly recovers waste products by withholding consumer postage, and Dell also relies on a self-built logistics system. Apple recycled its products through authorized retailers, while IBM commissioned third-party recyclers to undertake its global recycling business. Nevertheless, “low recycling efficiency, high recovery cost” is still the major problem facing enterprises. Enterprises realize that the correctness of the choice of recycling mode is very important to improve the waste recycling rate and promote the development of the CLSC. So, “how to collect and dispose of waste products reasonably and efficiently, and form a certain batch to generate economies of scale?” This is still one of the core issues of corporate practice and academic research.14

Obviously, the government has become increasingly prominent in the recycling process of waste products.15,16 Many countries develop preferential or subsidy policies to encourage relevant enterprises to participate in waste recycling. For example, to enhance awareness of manufacturer sustainability, Europe, Japan, and so forth, have issued regulations on government financial subsidies: India subsidies LED lights; the United States subsidies around $4000 per scrap car; China implements “trade-in” subsidy policy. Related studies have also shown that the government can influence market demand and rate of return through taxation and allocation of subsidies.17–19 However, does that mean that the higher the government subsidies, the more favorable? It is necessary to explore the impact of subsidies on CLSC performance.

In addition, due to their “low carbon,” “green,” or other characteristics, reproduces are gradually favored by environmental protection consumers, and the low carbonization of products will gradually become a measure of enterprise product differentiation.20–22 Gungor and Gupta23 and Linton et al.24 first discussed product recycling and manufacturing from an environmentally conscious perspective. CLSC is necessary to be consumer-centered and always pay attention to the changes of the “low-carbon will” in the consumer market.25 Moreover, we innovatively combine the low-carbon supply chain with the CLSC, assuming that manufacturers implement carbon emission reduction behavior in the recycling process, and explore the influence of drivers from consumer groups on the low-carbon practice of supply chain recycling and remanufacturing.

To sum up, studies related to CLSC are vast in numbers such as pricing decisions and profit distribution. While we believe that there is a lack of research on recycling strategy in the CLSC that introduces low-carbon factors and government subsidies. Specifically, we will mainly investigate the following questions in this paper:

1. Can a single recycling model achieve efficient recycling?
2. How does the government subsidy price affect the selection of recycling modes and recycling efficiency?
3. What is the impact of consumers' low-carbon preference on manufacturers' carbon emission reduction activities?

With the environment-friendly low-carbon CLSC, this paper constructs the situation of centralized and decentralized decisions (manufacturer recovery, retailer/third-party recovery) to study the influence law of consumer low-carbon preference and government subsidies on the CLSC, to seek the optimal recovery model. Finally, the effectiveness and utility of the proposed model are verified by numerical examples.

The innovations and practice value of our research are mainly embodied in the following aspects: (1) Considering that consumers' preference for low-carbon products can be closer to the actual situation of consumers' increasing environmental awareness. (2) It is assumed that the manufacturer has the awareness of independent emission reduction in the process of producing new products and recycling and remanufacturing, which is more in line with the current low-carbon and environmentally friendly business practice background. (3) Combining government subsidies and consumer low-carbon preference behaviors to discuss the optimal recycling mode of supply chain members will help to effectively integrate low-carbon supply chains with CLSCs. On the one hand, this paper is helpful for enterprises to find appropriate recycling models to increase the recycling and remanufacturing rate of old products and manufacturers' investment in carbon emission reduction. On the other hand, the proposal to
improve the government subsidy mechanism was put forward.

2 | LITERATURE REVIEW

In this part, three main literature streams are sorted out as follows: (1) Recycling model of CLSC. (2) Government subsidies in CLSC. (3) Research on supply chain considering consumers’ preference.

2.1 | Research on the recycling model of CLSC

The Stackelberg Game is often used to study the topic of CLSC pricing or profit allocation.26 Regarding the recycling strategy, scholars mainly take the manufacturer as the leader to study the recycling of waste products through reverse channels when manufacturers, retailers, or third-party recyclers recycle independently.27–29 Specifically, Savaskan et al. showed that the retailer collection model is the most effective choice for manufacturers. Choi and Li30 studied the CLSC performance of manufacturers, retailers, and third parties as market leaders, respectively. The results show that the CLSC of retailers as a market leader performs better than the traditional supply chain model led by the manufacturer/recycler. Modak et al.31 believe that third-party participation in second-hand product collection activities is always disadvantageous. Zheng et al.32 studied manufacturers and retailers to obtain more profits in Model M and Model R. Similarly, many scholars have proposed online/offline dual-channel recycling, which compares centralized decision-making with manufacturing-led decentralized decision-making to arrive at the optimal decision.33,34

Therefore, our research also uses Stackelberg Game to solve the three reverse channel models: (a) manufacturer’s collection model; (b) retailer’s collection model, and (c) third-party collection model, and compare the decision variables under centralized decision-making and decentralized decision-making.

2.2 | Research on CLSC considering government subsidies

Generally, manufacturers and retailers pursue the maximization of profits and lack the autonomy of recycling and remanufacturing behaviors, so they need sufficient external motivation to stimulate. The design of government subsidies has a great impact on the operation efficiency of the CLSC, so scholars gradually pay attention to the impact of this factor on recycling decisions.35–37

1. Scholars initially discuss whether it is necessary for the government to provide subsidies. For example, Mitra and Webster16 studies found that government subsidies could stimulate the development of the remanufacturing industry, which worked better for manufacturers and manufacturers. Gu et al.38 studied the optimal production strategy of electric vehicle manufacturers under government subsidies and battery recycling under the condition of uncertain market demand. The results show that the increase of subsidies can improve the manufacturer’s optimal production and expected utility.

2. with regard to the types of subsidies, Wang et al.39 explored the impact of subsidy policies on the development of China’s recycling and remanufacturing industry by simulating China’s auto parts industry, and introduced four subsidy policies: initial subsidy, recycling subsidy, R&D subsidy, and production subsidy. Gong et al.,40 introduced the influence of procurement subsidy (PS) and disassembly subsidy (DS) on the remanufacturing CLSC of manufacturers and disassembly enterprises and found that DS reduced the system profit. In fact, different subsidy objects will have different policy effects. Jena et al.’s41 research show that to maximize channel profits and total surplus, the government should choose manufacturers as subsidies.

3. Some scholars have studied the strength and methods of government subsidies. Zhao et al.42 established different CLSC pricing models for the government’s strategies of adopting different subsidies (consumers, retailers, manufacturers, or third-party recyclers). The results show that the government should increase subsidies for battery recycling of electric vehicles and urge electric vehicle enterprises to assume responsibility for battery recycling.43 Liu et al.44 comprehensively sorted out the government subsidy objects in the CLSC. Research shows that when government funds are limited, medium subsidy levels can be set. Subsidizing third parties can stimulate the recycling of scrap products, but it is unfavorable to manufacturers.45 The latest literature mostly focuses on the impact of government subsidies on supply chain profit distribution.45,46

Wang et al.47 believe that public policy has a far-reaching impact on the low-carbon supply chain, and consider the economic irrational factors that affect decision makers, such as altruistic preference, social responsibility, fair attention, which are the same as the low-carbon consumption preference studied in this paper, and use Stackelberg Game to solve it. Their views are as follows: (1) The intervention of the government subsidy mechanism will bring new changes to the operation of CLSC. For example, the government should
increase subsidies as much as possible within the budget to increase the profits of its members. At the same time, the government should also formulate subsidy policies aimed at making up for retailers’ recovery costs to encourage retailers to participate in the recovery. (2) In addition, the concept of “e-clsc” has been innovatively put forward, and how profits and recoveries change over time under the reward and punishment mechanism and altruistic preference mechanism has been deeply discussed. (3) Moreover, the conclusion that “government subsidies improve the overall operational efficiency of the supply chain and the total social surplus” is reached by discussing the impact of government subsidies and remanufacturers’ altruistic preferences on decision-making.

It can be seen that government subsidies play an important role in CLSC research, and the policy environment is also an area where research is very focused. However, some studies only consider the impact of government subsidies on CLSC pricing when a single entity is responsible for recycling.

### 2.3 Research on supply chain considering consumers’ preference

Most of the research, based on different consumer preferences (such as consumer willingness to pay, consumer environmental protection preference, remanufacturing product recognition, product green, etc.), will gradually combine different government subsidy policies with consumer preference behavior. Zhao et al. established a decision model that considers consumer preference for remanufacturing products, studying the pricing decision of remanufacturing products and the joint decision issue of subsidy share between remanufacturers and consumers. Hong et al. believe through research that the higher the consumer preference for remanufactured products, the higher the wholesale and retail price of remanufactured products, and the higher the recycling price of old products. As the consideration of a low-carbon environment in the reverse supply chain has become one of the hot issues, Xu and Wang added consumers’ low-carbon preferences into the analysis framework and established a new profit distribution mechanism to coordinate the distribution of the supply chain. However, the existing literature lacks a combination of government subsidies and consumer low-carbon preference behaviors and studies the decision-making behaviors of enterprises and governments for different subsidy objects, especially the lack of research on recycling strategies that consider both factors in a low-carbon context.

In general, (1) research on the supply chain in the low-carbon context mostly considers the pricing mechanism and coordination mechanism of the forward supply chain but does not consider the decision-making issues of recycling and remanufacturing of waste products in reverse logistics. (2) CLSC research focuses on government subsidies and types of subsidies, and gradually compares and analyzes the impact of differences in subsidies on CLSC decision-making. (3) In addition, some scholars conduct research on CLSC decision-making from the perspective of consumer preferences affecting market demand. However, government subsidies and consumers’ low-carbon preference behaviors are rarely combined, and the decision-making behaviors of enterprises and governments are studied for different subsidy objects. In particular, there is a lack of research on recycling strategies that consider both factors in a low-carbon context.

### 3 MODEL

#### 3.1 Problem description and assumptions

The related parameters are described in Table 1.

In view of the production operation and recycling problems of low-carbon manufacturers, this study comprehensively considers the impact of consumers’ low-carbon preference on the market demand for low-carbon products and the willingness of government subsidies on the CLSC enterprises to participate in recycling, remanufacturing, and emission reduction. The model of enterprise recycling is constructed, namely, that the manufacturer is directly responsible for recycling or entrusting retailers/third-party recyclers to indirectly recycle waste products from consumers, each undertaking the recovery costs and enjoying government subsidies according to the amount of recovery. The equilibrium strategy of the CLSC under the three game modes is obtained. This section shows the construction of a model in which manufacturers, retailers, and third-party recyclers are responsible for recycling respectively, as shown in i, ii, and iii in Figure 1.

**Suppose 1:** Manufacturers and retailers monopolize recycling in a single cycle. All members of the supply chain share information, and they are all risk-neutral and completely rational.

**Suppose 2:** Manufacturers are willing to reduce carbon emissions. There is no big difference between the performance and quality of new products and remanufactured products. Within a reasonable range, consumers have a low-carbon preference, and the degree of...
preference affects the market demand for products. According to the linear demand function model proposed by Pazoki et al., it is assumed that product demand is a function of product price and low-carbon level as follows:

\[ Q_i = a - w_i + \varepsilon e, \tag{1} \]

where, \( a \) is the potential market demand, \( a > 0; \varepsilon \) is the low-carbon preference of consumers; \( e \) is the level of carbon emission reduction.

**Suppose 3:** Assume that \( p_i \) and \( w_i \) are the wholesale and retail price of the product, and \( i = \{1, 2, ..., n\} \). In addition, \( b \) is the market recycling price of the enterprise facing consumers; \( t \) is the unit price of the manufacturer’s purchase of recycled products from retailers or third places. The unit production cost \( c_{n} \) is greater than the remanufacturing cost \( c_{r} \), so \( \Delta = c_{n} - c_{r} > 0 \) represents the cost saved per unit of recycling remanufactured products. To ensure the economy of recycling and remanufacturing activities, there is \( \Delta \geq t > b > 0 \). If \( \Delta \) is larger, it means that the manufacturer’s ability to carry out remanufacturing is stronger and the enterprise can, therefore, obtain higher additional profits.

| Variable | Description | Variable | Description |
|----------|-------------|----------|-------------|
| \( a \)  | Potential market demand | \( h \)  | Coefficient of Recovery cost |
| \( Q \)  | Market demand | \( k \)  | Coefficient of carbon emission reduction cost |
| \( p \)  | Wholesale price | \( E \)  | Fixed cost of carbon emission reduction |
| \( w \)  | Retail price | \( L \)  | Recovery of fixed costs |
| \( c_{n} \) | Unit production cost | \( s \)  | Unit subsidy price |
| \( c_{r} \) | Unit remanufacturing cost | \( \tau \) | rate of recovery |
| \( \varepsilon \) | Low carbon preference | \( \Delta \) | Remanufacturing cost advantage |
| \( e \)  | Carbon emission reduction efforts | \( \pi_M \) | Manufacturer’s profit |
| \( b \)  | Recovery price | \( \pi_R \) | Retailer’s profit |
| \( t \)  | Unit transfer price | \( \pi_G \) | Overall profit of closed-loop supply chain |

**FIGURE 1** Closed-loop supply chain model under a single recycling model. There are some assumptions: i. The model is directly recycled by the manufacturer. ii. Retailer recycling model commissioned by the manufacturer. iii. A third-party recycling model commissioned by the manufacturer.
Suppose 4: Manufacturers, retailers, or third-party recyclers collect waste products from consumers at a recycling rate $\tau$, and all recovered waste products are used for remanufacturing.

Suppose 5: The manufacturer’s carbon emission reduction cost is $E = \frac{1}{2}ke^2$ and $k$ is the manufacturer’s carbon emission reduction cost coefficient. And $k > 0$ shows that the cost of carbon emission reduction increases rapidly with the increase of carbon emission reduction level, that is, in the actual production process of enterprises, carbon emission reduction production activities cannot be carried out indefinitely. Similarly, the fixed cost of enterprises participating in recovery activities is $L = \frac{1}{2}hr^2$, and $h$ is the recovery cost coefficient. And $h > 0$ also shows that enterprises cannot rely too much on recycled products for production and manufacturing, and it is uneconomical to invest too much to improve the recovery rate.

Suppose 6: To promote the recycling of waste products, the government adopts subsidies for the recycling behavior of enterprises. It is assumed that the subsidy price of government units for recycled products under different recycling situations is $s$.

3.2 Recycling model based on Stackelberg Game

To simplify the calculation, let $B = (s + t - b)$, $C = (\Delta - t)$, and $A = B + C = (\Delta - b + s)$.

1. Centralized decision model

In this model, retail price is $w$, recovery rate is $\tau$, and carbon emission reduction effort level is $e$. The total profit of CLSC is shown in the formula below:

$$\max \pi_{CS} = [w - c_n + (\Delta + s - b)\tau](a - w + \varepsilon e) - \frac{1}{2}ke^2 - \frac{1}{2}hr^2. \tag{2}$$

Find the first-order partial derivative of Equation (2) to retail price $w$ and recovery rate $\tau$ as shown in the following formula:

$$\frac{\partial \pi_{CS}}{\partial w} = a + \varepsilon e - 2w + c_n - A\tau, \tag{3}$$

$$\frac{\partial \pi_{CS}}{\partial \tau} = A(a + \varepsilon e - w) - hr. \tag{4}$$

According to the $H\pi_{CS} = \begin{bmatrix} -2 & -A \\ -A & -h \end{bmatrix}$ of retail price $w$ and recovery rate $\tau$, we know that $|H_{11}| = -2 < 0$, and when $2h - A^2 > 0$, $|H_{22}| > 0$. So, $H\pi_{CS}$ is negative definite, that is, there are optimal $w$ and $\tau$ leads to the maximum of $\pi_{CS}$. Let $\frac{\partial \pi_{CS}}{\partial w}$ and $\frac{\partial \pi_{CS}}{\partial \tau}$ be 0 and solve simultaneously. Substitute the obtained value into (2) calculate the first-order partial derivative of the carbon emission reduction effort level $e$, which includes as shown in the formula below:

$$\frac{\partial \pi_{CS}}{\partial e} = \frac{eh(a + \varepsilon e - c_n)}{2h - A^2} - ke. \tag{5}$$

When $\frac{\partial^2 \pi_{CS}}{\partial e^2} = he^2 - k(2h - A^2) < 0$, it has optimal carbon reduction levels $e^*$ to maximize profits in the supply chain. The optimal solutions are shown in the following formulas

$$e^* = \frac{he(a - c_n)}{k(2h - A^2) - he^2}, \tag{6}$$

$$w^* = \frac{k(h - A^2)a + h(k - \varepsilon^2)c_n}{k(2h - A^2) - he^2}, \tag{7}$$

$$\tau^* = \frac{Ak(a - c_n)}{k(2h - A^2) - he^2}. \tag{8}$$

To ensure that the equilibrium solutions are all positive, there are constraints as in the following formula:

$$\begin{cases} 
  k > \frac{hc_n e^2}{(h - A^2)a + hc_n}, \\
  k > \frac{he^2}{2h - A^2}, \\
  2h - A^2 > 0.
\end{cases} \tag{9}$$

2. The model is directly recycled by the manufacturer (Model 1)

The manufacturer first determines the wholesale price $p_1$, and then the retailer sells products to consumers at the retail price $w_1$. The manufacturer directly recycles waste products from consumers at the recovery rate $\tau_1$ and recovery price $b$ to form a CLSC, in which the government gives full subsidies to the manufacturer according to the recovery amount. The profit functions are shown in the following formulas:

$$\max \pi_M^1 = [p_1 - c_n + (\Delta - b + s)\tau_1]$$

$$\quad(a - w_1 + \varepsilon e_1) - \frac{1}{2}ke_1^2 - \frac{1}{2}h\tau_1^2, \tag{10}$$

$$\max \pi_M^1 = (w_1 - p_1)(a - w_1 + \varepsilon e_1). \tag{11}$$
Similarly, according to the Backward induction, the retail price $w_1$ is obtained from the retailer function and then substituted into the manufacturer function to obtain the Hessian matrix of wholesale price and recovery rate

$$H\pi^R_{t} = \begin{bmatrix} -1 & -\frac{A}{2} \\ -\frac{A}{2} & -h \end{bmatrix}.$$

The following can be obtained by the simultaneous solution:

$$p_1 = \frac{(2h - A^2)(a + \varepsilon_1) + 2hc_n}{4h - A^2}, \quad (12)$$

$$\tau_1 = \frac{A(a + \varepsilon_1 - c_n)}{4h - A^2}, \quad (13)$$

$$w_1 = \frac{(3h - A^2)(a + \varepsilon_1) + hc_n}{4h - A^2}. \quad (14)$$

Then, substitute formula (10) for the first-order derivation of the low-carbon effort level to obtain the optimal amount $e_1$, as shown in the following formula:

$$e_1^* = \frac{h(e(a - c_n))}{k(4h - A^2) - h\varepsilon^2}. \quad (15)$$

Therefore, the optimal wholesale price, retail price, and recovery rate are shown in the formulas below:

$$p_1^* = \frac{k(2h - A^2)a + h(2k - \varepsilon^2)c_n}{[k(4h - A^2) - h\varepsilon^2]}, \quad (16)$$

$$w_1^* = \frac{k(3h - A^2)a + h(k - \varepsilon^2)c_n}{[k(4h - A^2) - h\varepsilon^2]}, \quad (17)$$

$$\tau_1^* = \frac{ka(a - c_n)}{[k(4h - A^2) - h\varepsilon^2]}. \quad (18)$$

3. Retailer recycling model commissioned by the manufacturer (Model 2)

The manufacturer first determines the wholesale price $p_2$. The retailer sells products to consumers at retail price $w_2$ and directly recycles waste products from consumers at recovery rate $\tau_2$ and recovery price $b$. The manufacturer then buys back the waste products from the retailer at the transfer payment price $t$ for remanufacturing, forming a CLSC, in which the government fully subsidizes the retailer. The profit functions are shown in the following formulas:

$$\text{max } \pi^R_{t} = [p_2 - c_n + (\Delta - t)\tau_2](a - w_2 + \varepsilon_2) - \frac{1}{2}ke^2 \quad (19)$$

$$\text{max } \pi^M_2 = [w_2 - p_2 + (s + t - b)\tau_2](a - w_2 + \varepsilon_2) - \frac{1}{2}he^2 \quad (20)$$

Backward induction is also used to solve questions. According to the first-order partial derivatives of Equation (20) to $w_2$ and $\tau_2$, and then from the Hesse matrix $H\pi^M_{t} = \begin{bmatrix} -2 & -B \\ -B & -h \end{bmatrix}$, it is known that the retailer profit function is a strictly concave function, where $2h - B^2 > 0$. Then, the values of formulas (21–23) are obtained.

$$w_2 = \frac{(h - B^2)(a + \varepsilon_2) + hp_2}{2h - B^2}, \quad (21)$$

$$\tau_2 = \frac{B(a + \varepsilon_2 - p_2)}{2h - B^2} \quad (22)$$

$$p_2 = \frac{(2h - B^2 - BC)(a + \varepsilon_2) + (2h - B^2)c_n}{4h - 2B^2 - 2BC}. \quad (23)$$

Then the first-order derivative of the emission reduction effort level is obtained for the manufacturer’s profit function to obtain the optimal amount.

$$e_2^* = \frac{h(e(a - c_n))}{[2k(2h - B^2 - BC) - h\varepsilon^2]}. \quad (24)$$

By substituting the optimal wholesale price, retail price, recovery rate, and emission reduction effort level into the manufacturer profit formula (19), it can be seen that the manufacturer’s profit increases with the increase of unit repurchase price $t$. Therefore, assuming that the unit price of recycled products purchased by the manufacturer from the retailer is its upper bound $t$, $t_{R}^{*} = \Delta$ is substituted into the above formula, and the optimal solution can be obtained, as shown in the following formulas:

$$p_2^* = \frac{k(2h - A^2)(a + c_n) - h\varepsilon^2c_n}{[2k(2h - A^2) - h\varepsilon^2]}, \quad (25)$$

$$w_2^* = \frac{k(3h - 2A^2)a + h(k - \varepsilon^2)c_n}{[2k(2h - A^2) - h\varepsilon^2]}, \quad (26)$$

$$\tau_2^* = \frac{2kA(a - c_n)}{2k(2h - A^2) - h\varepsilon^2}, \quad (27)$$

$$e_2^* = \frac{h(e(a - c_n))}{[2k(2h - A^2) - h\varepsilon^2]}. \quad (28)$$
where, \( 2k(2h - A^2) - h\varepsilon^2 > 0 \).

4. Third-party recycling mode entrusted by the manufacturer (model 3)

The manufacturer first decides the wholesale price \( p_3 \). The retailer sells the product to the consumer at the retail price \( w_3 \). The third-party recycler directly recycles the waste products from the consumer at the recycling rate \( \tau_3 \) and the recycling price \( b \). The manufacturer then pays the transfer price \( t \) from the consumer. The third party recycling mode entrusted by the third party and the recycling price \( w \).

\[
\Delta - \text{the price transferred to a third party recycling mode entrusted by the third party and the recycling price } \]

The optimal decisions under different recycling models are shown in Table 2.

**Theorem 1.** Manufacturer’s carbon emission level is positively correlated with government subsidies and consumers’ low-carbon preferences. In Model 2, the manufacturer has the highest willingness to reduce emissions. The carbon emission reduction levels of the three recycling methods are shown in Table 2.

**Proof.**

We know that

\[
e_s^* = \frac{2h\varepsilon(a - c_n)}{k(8h - A^2) - 2h\varepsilon^2}.
\]

so let \( g_1 = k(4h - A^2) - h\varepsilon^2 \), \( g_2 = k(4h - 2A^2) - h\varepsilon^2 \), and \( g_3 = k\left(4h - \frac{1}{2}A^2\right) - h\varepsilon^2 \).

From the optimal decision under different recycling modes, we know that \( e_s^* > e_1^* > e_3^* \).

**Theorem 2.** Theorem 1 shows that the manufacturer needs to spend a lot of cost on carbon emission reduction activities, so the wholesale price in Model 2 is also the highest and government subsidies will not affect this result. In Models 1 and 3, government subsidies will affect the wholesale price of the manufacturer. The wholesale prices of the three models have the following relationship: \( p_3^* > p_1^* > p_3^* \).

**Proof.**

\[
p_3^* - p_1^* = \frac{A^2(a - c_n) + (4h - A^2)\varepsilon e_s^* - (4h - 2A^2)\varepsilon e_1^*}{2(4h - A^2)}.
\]

| TABLE 2 | Values of decision variables under single recycling mode |
| --- | --- | --- |
| **Model 1** | **Model 2** | **Model 3** |
| \( p_3^* \) | \( k(2h - A^2)a + h(2k - e)\varepsilon c_n \) | \( k(2h - A^2)a + h(2k - e)\varepsilon c_n \) | \( 2k(4h - A^2)a + 2k(2h - e^2)c_n \) |
| \( w_3^* \) | \( k(2h - A^2)a + h(4h - A^2) - h\varepsilon^2 \) | \( k(2h - A^2)a + h(4h - A^2) - h\varepsilon^2 \) | \( k(2h - A^2)a + 2h(k - e^2)c_n \) |
| \( \tau_3^* \) | \( kA(a - c_n) \) | \( 2kA(a - c_n) \) | \( k(4h - A^2)a - h\varepsilon^2 \) |
| \( e_1^* \) | \( \frac{h\varepsilon(a - c_n)}{k(4h - A^2) - h\varepsilon^2} \) | \( \frac{h\varepsilon(a - c_n)}{k(4h - A^2) - h\varepsilon^2} \) | \( \frac{2h\varepsilon(a - c_n)}{k(4h - A^2) - h\varepsilon^2} \) |
| \( t_3^* \) | \( \Delta \) | \( \Delta + b - s \) |
Because $a - c_n > 0$ and $e_2^* > e_1^*$, so $p_2^* - p_1^* > 0$. Similarly, where $e_2^* > e_3^*$ and $e_4^* > e_5^*$, we can see that:

$$p_1^* - p_3^* = \frac{4h(4h - A^2)a + 2hA^2c_n + (32h^2 - 12hA^2)\varepsilon}{(4h - A^2)(8h - A^2)} > 0.$$

$p_1^* - p_3^*$ is proven.

**Theorem 3.** It can be seen that retail prices will be affected by consumers’ low-carbon preferences. When $\varepsilon \in (0, \sqrt{k})$, the retail price is the highest in Model 1 and the lowest in Model 3. When $\varepsilon \in (\sqrt{k}, +\infty)$, the retail price is the highest in Model 3 and the lowest in Model 1. The retail price size is as follows:

1. When $\varepsilon \in (0, \sqrt{k})$, $w_1^* > w_2^* > w_3^*$.
2. When $\varepsilon \in (\sqrt{k}, +\infty)$, $w_2^* > w_3^* > w_1^*$.

**Proof.**

It can be seen that:

$$w_1 - w_2 = \frac{A^2hk(a - c_n)(k - \varepsilon^2)}{(A^2k + h(\varepsilon^2 - 4k))[(A^2k + h(\varepsilon^2 - 4k)]},$$
$$w_2 - w_3 = \frac{3A^2hk(a - c_n)(k - \varepsilon^2)}{(2A^2k + h(\varepsilon^2 - 4k))[(A^2k + 2h(\varepsilon^2 - 4k)]},$$
$$w_1 - w_3 = \frac{A^2hk(a - c_n)(k - \varepsilon^2)}{(A^2k + h(\varepsilon^2 - 4k))[(A^2k + 2h(\varepsilon^2 - 4k)]}.$$

So, the retail price is related to $k$ and the degree of preference $\varepsilon^2$.

**Theorem 4.** The recycling rate will also be affected by consumers’ low-carbon preference. When $\varepsilon \in (0, 2\sqrt{k})$, The recovery rate is highest in Model 2 and lowest in Model 3. When $\varepsilon \in (2\sqrt{k}, +\infty)$, The recovery rate is highest in Model 3 and lowest in Model 2. The specific relationship of the recovery rate is as follows:

1. When $\varepsilon \in (0, \sqrt{k})$, $\tau_0^* > \tau_1^* > \tau_2^*$.
2. When $\varepsilon \in (2\sqrt{k}, +\infty)$, $\tau_0^* > \tau_1^* > \tau_2^*$.

**Proof.**

It can be seen that:

$$\tau_0^* = \frac{2kA(a - c_n)}{2k(4h - A^2) - 2he^2},$$
$$\tau_1^* = \frac{2kA(a - c_n)}{2k(2h - A^2) - he^2}$$
and
$$\tau_2^* = \frac{2kA(a - c_n)}{2k(8h - A^2) - 4he^2}.$$

Let

$$f_1 = 2k(4h - A^2) - 2he^2, f_2 = 2k(2h - A^2) - he^2, f_3 = 2k(8h - A^2) - 4he^2,$$

we can know that

$$f_1 - f_2 = h(4k - \varepsilon^2), f_1 - f_3 = 2h(\varepsilon^2 - 4k), f_2 - f_3 = 3h(\varepsilon^2 - 4k).$$

When $4k - \varepsilon^2 > 0$, there is $f_3 > f_1 > f_2$, then $\tau_0^* > \tau_1^* > \tau_2^*$.

When $4k - \varepsilon^2 < 0$, there is $f_2 > f_1 > f_3$, then $\tau_0^* > \tau_1^* > \tau_2^*$.

**Theorem 4.** The manufacturer’s unit transfer price $t_R^* = \Delta$ in Model 2 is greater than the price $t_R^* = \frac{\Delta + b - s}{2}$ transferred by the manufacturer to a third-party recycler in Model 3.

**Proof.**

$$t_R^* - t_R^* = \Delta - \frac{\Delta + b - s}{2} = \frac{\Delta + s - b}{2} > 0.$$

**4 | NUMERICAL ANALYSIS**

Using Mathematica 12.0, this paper makes a numerical analysis of the four models and takes the government subsidy price $a$ and consumers’ low-carbon preference $B$ as variables to analyze the impact on the wholesale price, retail price, recovery rate, carbon emission reduction level, each member of the supply chain and the overall profit. We assume that $a = 100$, $c_n = 10$, $c_r = 7$, $\Delta = 3$, $k = 120$, $h = 60$, $s \in (0, 1)$, $\varepsilon \in (0, 8)$.
5 | PROFIT OF CLSC

The total profit of the CLSC is positively correlated with government subsidies and consumers' low-carbon preference, but it is more affected by consumers' low-carbon preference. Specifically, the total benefit of the CLSC of centralized decision-making is higher than that of decentralized decision-making. In addition, the overall performance of Model 2 is the highest, and the total profit of Model 1 is slightly higher than that of Model 3. From the perspective of total profit, it is the best choice for the manufacturer to commission the retailer for recycling (as shown in Figure 1i).

The profit of manufacturers in Model 2 increases with the increase of government subsidies, but the profit of manufacturers in Model 1 and Model 3 is less affected by government subsidies. In addition, when the government subsidy is high, the profit of the manufacturer entrusting the retailer to recycle is much greater than the other two situations. At this time, Model 2 is more profitable for the manufacturer (as shown in Figure 1ii).

In Model 1 and Model 3, the retailer's profit increases with the increase in government subsidy price, but the retailer's profit in Model 2 is negatively correlated with the government subsidy price. When the government provides the same subsidy price, the retailer's profit in Model 1 is greater than that in Model 3, and both are greater than that in Model 2 (as shown in Figure 1ii).

It can be seen from Figure 1 that the increase of consumers' awareness of low-carbon and environmental protection is profitable for the CLSC. At the same time, the higher consumers' low-carbon preference, the manufacturer entrusts retailers to recycle waste products, which is the best for the CLSC. Retailers are closest to the consumer market, and their profits are most affected by the change of consumers' low-carbon preference (as shown in Figure 1iii).

6 | PRODUCT PRICE

The wholesale price of Model 1 and Model 3 is negatively correlated with government subsidies, and the decline of wholesale price of Model 1 is greater than that of the third-party recycler (Model 3). However, the wholesale price of Model 2 is hardly affected by government subsidies. In addition, we can also see that when the subsidy price is the same, the wholesale price relationship of the three models is \( p_2^* > p_1^* > p_3^* \). As shown in Figure 2i, the wholesale price is positively correlated with consumers' low-carbon preference. It shows that the increase in consumers' low-carbon preference has prompted manufacturers to increase their investment in carbon emission reduction costs while increasing the output of low-carbon products. However, this also makes the production cost of low-carbon products gradually increase, so manufacturers increase the wholesale prices of low-carbon products to seek greater profits.

When consumers have the same low-carbon preference for products, the wholesale price for centralized decision-making is the lowest. It shows that the CLSC has the ability to bear the cost of abatement in centralized decision-making, and obtain a larger market share through lower sales prices. In decentralized decision-making, we can find that the degree of change in the sales price of Model 1 with consumers' low-carbon preference and the specific price are consistent with those of Model 3. This indicates that the revenue of the retailers in the two models only comes from selling low-carbon. If a manufacturer raises the wholesale

\[\text{FIGURE 2} \quad \text{The impact of consumer low-carbon preferences and government subsidies on closed-loop supply chain profits}\]
price of a product to compensate for the high cost of carbon emission reduction, the retailer also raises the selling price, allowing consumers to bear part of the cost.

In Model 2, when consumers' low-carbon preference increases, low-carbon awareness will also promote the increase in product recycling. Not only are there government subsidies, but the retailer will also receive transfer payment profits from the manufacturer, so it can sell products at relatively low prices in the three models and make profits at the same time. At this time, the retail price is \( w_i^* > w_j^* > w_k^* \) (as shown in Figure 2ii).

It can be seen that market demand increases with the increase of government subsidies. The market demand is the largest when the centralized decision is made, which indicates that when the government concentrates on subsidizing the supply chain, the retail price is the lowest at this time, and the price advantage is obvious. Consumers will buy new products and remanufactured products at low prices. In Model 2, retail prices and market demand vary the most with government subsidies, which indicates that retailers' profits are mainly derived from selling products, reselling waste products, and government subsidies. In Model 2, retailers reduce prices to expand sales, not only can obtain direct profits, but also expand the recycling volume of waste products. In other words, when the government subsidizes manufacturers and retailers, their prices and market demand are not greatly affected by changes in subsidized prices. In Model 1 and Model 3, retailers usually adjust their prices slightly according to the reduction in the wholesale price provided by the manufacturer, so their sales are less affected.

### 7 PRODUCT RECOVERY RATE

The recovery rate is positively correlated with government subsidies and consumers' low-carbon preferences. Specifically, when the CLSC centralized the decision-making process, the recovery rate of waste products coincides with the change curve of Model 2's recovery rate, the two types of models have the highest recovery rate, and Model 3 has the lowest recovery rate. The variation range of recovery is Model 2 > Model 1 > Model 3. This shows that retailers are more willing to obtain government subsidies and transfer income paid by manufacturers by increasing recycling activities. However, with the strong preference for low-carbon consumption, the recovery rate of centralized decision-making is significantly higher than that of Model 2, which is because the CLSC is more able to bear the recovery cost. In Model 1 and Model 3, the increase in consumers' low-carbon preference has little effect on the recovery rate (as shown in Figure 3).

### 8 MANUFACTURER'S CARBON EMISSION LEVEL

It is assumed that manufacturers have active carbon emission reduction awareness in the production of new products and the remanufacturing of waste products. We know that the carbon emission reduction level is the highest when centralized decision-making. In decentralized decision-making, the carbon emission reduction level will increase slightly with the increase in government subsidy price. In Model 2, the results show that the selling price is the lowest and the market demand is the highest. Both retailers and manufacturers can obtain profits by reducing product prices and increasing volume. At this time, the manufacturer entrusts the retailer to carry out recycling can avoid the manufacturer's direct recycling cost. Consumers in the market have low-carbon consumption preferences. Therefore, manufacturers are willing to increase their investment in carbon emission reduction during the production process.

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**Figure 3** The impact of consumer low-carbon preferences and government subsidies on product prices
and endow products with low-carbon characteristics to attract more consumers and increase profits. Therefore, when consumers’ preference for low-carbon products is increasing, manufacturers will increase carbon emission reduction efforts, that is, they are willing to invest more costs in carbon emission reduction production (as shown in Figures 4 and 5).

9 | CONCLUSION AND POLICY IMPLICATIONS

Considering the single recovery mode of CLSC with government subsidies and consumers’ low-carbon preference, this paper obtains the equilibrium solutions of various models about each decision variable through centralized decision-making and decentralized decision-making, and analyzes and compares the wholesale price, retail price, recovery rate, carbon emission reduction level and profit of each member enterprise of CLSC, so as to obtain the optimal recovery channel under different conditions; Finally, through numerical analysis, the effectiveness of the model and the influence of various variables on the recovery decision-making of CLSC members are verified.

The following conclusions can be drawn:

1. Centralized decision-making is always better than decentralized decision-making
   (1) The overall performance of CLSC with centralized decision-making is much higher than that of decentralized decision-making. (2) For manufacturers, when they entrust retailers to recycle waste products, their own profits are the largest. The profit of entrusting a third party to recover is the lowest, and the higher the subsidy price of the government unit, the better. (3) However, for retailers, the model of manufacturers entrusting retailers is not conducive to retailers’ profits, and the more government subsidies, the better. Manufacturers directly undertake recycling activities, which is the best recycling mode for retailers.

2. Wholesale and retail prices are negatively correlated with government subsidies. Carbon emission reduction level and the recovery rate are positively correlated with government subsidy prices. When manufacturers choose retailers for recycling, the recovery rate is the highest, while the entrusted third party has the lowest recovery rate. Therefore, manufacturers can make profits by entrusting retailers to recycle. If the government gives retailers recycling subsidies, manufacturers and retailers, respectively, reduce prices to guide market demand. If the government increases subsidies, the model entrusted by manufacturers to retailers is more willing to adopt low price strategy to benefit consumers, and consumers are more willing to provide recycling of waste products.

3. Wholesale price, retail price, and carbon emission reduction level are positively correlated with consumers’ low-carbon preference. In addition, consumers have higher product carbon preferences and manufacturers are more willing to invest in carbon emission reduction to expand market capacity. Although the recycling rate is not affected by consumers’ low-carbon preference, the recycling rate when the manufacturer entrusts retailers or third parties to recycle is greater than the recycling rate when the manufacturer directly participates in recycling activities. This shows that the closer the recycling entity is to Consumers, their recycling rate is more susceptible to the low-carbon preference of their products.

Based on the findings of this study, the following management insights can be obtained:
1. This study suggests that members of CLSC enterprises should pay close attention to the environmental awareness and product preferences of consumers in the existing market. It is necessary for manufacturers to classify carbon emission reduction products or retailers to set sales labels for consumers to accurately identify the “low-carbon” attribute of remanufactured products, so as to expand demand. At the same time, the subjects closer to consumers are more vulnerable to their low-carbon preferences. Therefore, retailers can also stimulate market demand by increasing low-carbon advertising and marketing, but this part may involve the investment of low-carbon publicity costs, which can also be carried out as a research point in the future.

2. The government’s improvement of subsidy prices within a certain range is conducive to waste product recycling activities. This measure also helps manufacturers save costs to invest in carbon emission reduction manufacturing, and promotes the profits of each member of the CLSC and the overall profit. When determining the subsidy object and intensity ofCLSC enterprises, the government should consider the financial effects of different industries and reasonably determine the subsidy object and intensity when formulating corresponding policies. As the recycling industry is booming, the government should pay more attention to controlling the recycling proportion of different channels, such as online and offline multichannel and multicombination recycling. Of course, this is also a point that future research can be in-depth.

3. The effect of subsidizing third parties on the CLSC is not obvious. Therefore, the government should consider the financial effects of different targets and determine the targets and intensity of subsidies reasonably. Therefore, this study suggests that the government should preset the financial effect according to the characteristics of different industries and reasonably determine the subsidy object and intensity when formulating corresponding policies. As the recycling industry is booming, the government should pay more attention to controlling the recycling proportion of different channels, such as online and offline multichannel and multicombination recycling. Of course, this is also a point that future research can be in-depth.

4. The government should increase environmental protection publicity and cultivate consumers’ preference for low-carbon products. This can not only directly promote the profit of the CLSC system, but also side-effect the recycling rate and the manufacturer’s carbon emission reduction level. Specifically, recycling waste products can bring both economic and environmental benefits to society. As the main body of natural credibility and appeal, the government can release relevant documents and post slogans in public places such as online media, community properties, and consumer places to strengthen environmental protection publicity and cultivate consumers’ preferences for low-carbon products, which can not only dredge the path of “reverse supply chain” from the end to the source, It can also affect the recovery rate and the carbon emission reduction level of manufacturers.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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