



Research article

Stackelberg game analysis of carbon reduction label standards in agricultural supply chains: Impacts of consumer low-carbon preference and label recognition

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Abstract: In response to growing concerns over agricultural carbon emissions, carbon reduction label standards (CES) have emerged as a market-oriented policy tool to promote low-carbon transitions in supply chains. This study investigates the effects of consumers' low-carbon preference (CLP) and consumers' recognition of carbon reduction labels (CLR) on the effectiveness of CES within agricultural supply chains, considering two emission reduction strategies that are independent reduction by processors (i.e. Non-cooperative Strategy, NS model) and two-tier reduction by suppliers and processors (i.e. Tandem Strategy, TS model). Using Stackelberg game theory, we derive optimal pricing, emission reduction levels, profits, and environmental and social benefits under each model. Our analytical and numerical results reveal that stringent CESs enhance carbon reduction, profitability, and social benefits when CLR is high, particularly under two-tier emission reduction. Moreover, the comparative advantage of two-tier over independent reduction widens with increasing CLR. While higher CLP incentivizes greater emission reductions, its effects on profits and social benefits depend on its interaction with CES's stringency and the choice of reduction strategy. Notably, under high CLP, relaxed CES can yield higher firm profits and social benefits than strict standards. This study provides theoretical and practical insights for policymakers, firms, and consumers in designing and responding to carbon labeling policies.

Keywords: agricultural product supply chain; carbon reduction label standards; low-carbon preference; two-tier emission reduction; Stackelberg game

Mathematics Subject Classification: 91A80, 91B42, 91B76

1. Introduction

The agricultural sector accounts for one-fourth of global anthropogenic greenhouse gas emissions, ranking second only to electricity production in its carbon footprint and thus contributing significantly to global warming [1]. In response, governments have introduced carbon reduction policies to mitigate the impact of carbon emissions [2]. Among these policies, carbon labeling, as a market-oriented policy tool, has emerged as a key component of national carbon reduction strategies [3]. A carbon reduction label signifies that a product's lifecycle carbon emissions fall below a specified threshold. Consequently, the development of carbon reduction label standards (CES) is critical to the effective functioning of carbon reduction mechanisms and has become a focal point for global agricultural supply chain members and CES developers alike.

Consumers' preference for eco-friendly products is essential to the successful implementation of carbon labeling policies, with CES emerging as a vital instrument for fostering low-carbon consumption habits [4,5]. The effectiveness of CES is substantially shaped by consumers' low-carbon preferences (CLP). Nevertheless, research on how CLP influence CES's effectiveness remains scarce. Existing literature predominantly demonstrates that CLP significantly influence carbon reduction outcomes and purchasing behavior. For instance, Chen et al. [6] and Qiao et al. [7] posited that a proclivity for low-carbon living shapes consumers' purchasing patterns, steering them towards more sustainable product choices, which, in turn, positively impacts the pricing and market share of low-carbon goods. Bai et al. [8] highlighted the business potential of green products, noting that consumers' environmental consciousness is a key impetus for companies to advance the sustainability of their offerings. Xu et al. [9] revealed that consumers with heightened CLP exhibit a greater concern for environmental issues, with their purchasing decisions often swayed by carbon reduction labels. Those with a pronounced inclination towards low-carbon products are more inclined to select items bearing such labels, thereby incentivizing producers and supply chain actors to adopt greener practices. Chen et al. [6] also found that CLP can directly stimulate market demand for low-carbon products and indirectly spur enterprises to refine their production processes to align with this demand. Yao et al. [10] and Zhang et al. [11] indicated that CLP directly alter consumers' purchasing behavior, propelling companies to invest further in green products. Given these dynamics, uncovering the impact of CLP on CES is crucial for improving label design, raising consumer awareness, and expanding the low-carbon product market.

Carbon reduction label standards are formulated by various initiators based on their individual objectives. However, the credibility of these developers varies, leading to differing levels of consumer recognition of carbon reduction labels (CLR). Consequently, the effectiveness of CES is largely contingent upon CLR. Delmas and Lessem [12] highlighted the prevalence of "greenwashing" where companies set low standards for carbon reduction labels to overstate their environmental performance. Such tactics, often part of green marketing strategies, can mislead consumers and fail to deliver substantial emission reductions, thereby eroding consumer trust. The level of CLR directly influences consumers' behavior, alters the perceived value of carbon reduction labels to businesses and society,

and subsequently impacts the carbon reduction strategies of agricultural supply chain members. Delmas and Lessem [12] noted that higher CLR can stimulate the demand for low-carbon products. Courtat et al. [13] observed that in the European Union, the carbon reduction label enjoys high CLR due to stringent standards and transparent certification processes, which bolsters consumer confidence. Understanding the impact of CLR on CES's effectiveness is vital for devising more potent carbon reduction strategies. However, there is a dearth of research on how CLR influence corporate decision-making.

Additionally, the emission reduction strategies of agricultural supply chain actors significantly influence the efficacy of CES implementation. Given the high energy consumption and waste emissions associated with agricultural product production, the majority of scholarly work has concentrated on the carbon reduction efforts of processing entities. Du et al. [14] delved into the production optimization challenges for processors within the context of carbon management and sustainable development frameworks. Mardyana and Gour [15] demonstrated that investments by manufacturers in carbon reduction technologies not only enhance environmental performance but also yield economic benefits for supply chain participants. These investigations offer theoretical backing for agricultural product processors to implement diverse carbon management strategies.

However, carbon emissions are present at every stage of the agricultural supply chain, with suppliers being one of the primary contributors. Guo and Zhang [16] demonstrated that no-till planting and straw return during the agricultural growth phase can establish long-term carbon reduction and sustainable development mechanisms in agriculture. For instance, Mars works with cocoa farmers to promote climate-smart agricultural practices, reducing energy consumption during processing to lower the carbon footprint across the entire supply chain. PepsiCo has introduced sustainable emission reduction initiatives in its agricultural supply chain, partnering with farmers to adopt water conservation and reduced fertilizer use, while also enhancing processing to cut energy consumption. General Mills collaborates with farmers and suppliers to promote agricultural practices that minimize carbon emissions and boost energy efficiency across both the processing and production stages. These efforts exemplify the two principal emission reduction strategies available to supply chain participants, with one being independent abatement by processors and the other being two-tier abatement involving both processors and suppliers. The choice between these two strategies exerts different influence on the effectiveness of CES.

Comparing this study with relevant literature (Table 1), we found that the establishment of CES is regarded as a pivotal step in mitigating carbon emissions and advancing sustainable development. CLP, CLR, and the emission reduction strategies of agricultural supply chain actors all influence the effectiveness of CES implementation. Despite these advances, three research gaps persist. First, while CLP has been widely examined as a driver of green consumption, its interaction with CES's stringency remains underexplored. Most existing studies treat CLP as an exogenous factor that unilaterally boosts demand, yet they overlook how different CES levels moderate this effect on firms' profitability and societal welfare. Second, the role of CLR, which refers to consumers' trust in and recognition of carbon labels, has been largely neglected in quantitative modeling literature. Although Delmas and Lessem [12] and Courtat et al. [13] qualitatively highlighted the credibility issue, no study has formally incorporated CLR into a game-theoretic framework to analyze its impact on supply chain decisions. Third, the comparative performance of independent versus two-tier emission reduction strategies under CES has not been systematically investigated, especially when both CLP and CLR are considered simultaneously. Most of the research has focused on processors' unilateral abatement efforts, leaving the upstream suppliers largely unaddressed.

Table 1. Comparison of this study with related literature.

Literature	ASC	CES	Customer recognition		Emission reduction actor	
			CLP	CLR	supplier	processor
Qiao et al. [7]			○		○	○
Bai et al. [8]			○			○
Yao et al. [10]			○			○
Zhang et al. [11]			○			○
Jiang et al. [3]		○		○		
An et al. [17]		○	○			○
He and Sun [18]			○			○
Li et al. [1]	○		○			
Guo and Zhang [16]	○				○	
Alkaabneh et al. [2]	○	○	○			
Chen et al. [6]	○	○		○		
Wang et al. [19]	○		○			○
Zhang et al. [20]	○	○	○			
This study	○	○	○	○	○	○

Note: ASC, agriculture supply chain; CES, carbon reduction label standard; CLP, low-carbon preference; CLR, customers' recognition of carbon reduction labels.

This study fills these gaps by developing a Stackelberg game model that integrates CLP, CLR, and two distinct reduction strategies, independent reduction by processors (i.e. Non-cooperative Strategy, NS model) and two-tier reduction by suppliers and processors (i.e. Tandem Strategy, TS model), within a unified CES framework. In the NS model, processors independently bear the abatement responsibility, whereas in the TS model, both suppliers and processors engage in collaborative mitigation. Drawing on Stackelberg game theory, we derive optimal decisions for all parties and conduct comparative analyses to evaluate the economic, environmental, and social outcomes. We aim to answer three questions. First, how do different CES's stringency levels affect pricing, emission reduction, profitability, and social benefits in the agricultural supply chain? Second, how do CLP, CLR, and the choice of emission reduction strategy (NS versus TS) interact to shape the effectiveness of CES? Third, under what conditions might relaxed CES outperform strict CES in terms of firm profits and social welfare?

By addressing these questions, we provide a comprehensive understanding of CES design and its implications for sustainable agricultural practices. The contributions of this study are threefold. First, we integrate both CLP and CLR into a unified demand function, capturing their interactive effects on market demand. This integration allows us to compare two distinct emission reduction strategies, NS and TS, under a CES framework, thereby offering theoretical guidance for strategy selection. Second, beyond confirming the intuitive result that stricter CES generally lead to higher carbon reductions, we uncover a nonmonotonic and context-dependent relationship. Specifically, under high CLP, relaxed CES can generate higher firm profits and social benefits than strict CES. This finding challenges the

conventional view that “stricter is always better” and reveals a boundary condition for CES design. Third, we identify an asymmetric effect of CLR and CLP on the performance between the NS and TS models. Specifically, as CLR increases, the advantage of two-tier reduction over independent reduction in terms of profits and environmental benefits widens monotonically. In contrast, as CLP increases, this advantage first narrows and then widens, revealing a previously undocumented dynamic in supply chain collaboration on emission reduction.

The remainder of this study is as follows. Section 2 outlines the assumptions and defines the pertinent parameters. Section 3 introduces the supply chain models with distinct emission reduction strategies. Section 4 presents a comparative analysis of these models. Section 5 substantiates the model through case studies. Finally, Section 6 synthesizes the findings and presents the conclusions.

2. Parameter description and assumptions

As depicted in Figure 1, this study constructs a supply chain model for agricultural products that includes both suppliers and processors. Suppliers, as upstream entities, provide the raw materials, which processors then transform into finished products, package, and sell to the market. To investigate the emission reduction strategies of supply chain members, we develop two models: NS and TS.

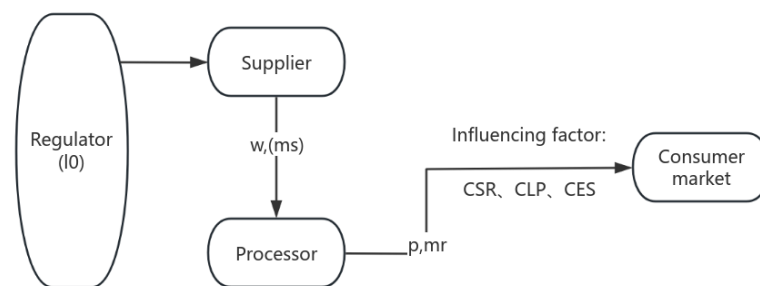


Figure 1. Flow chart of the agricultural product supply chain.

In the NS model, only processors make investments in emission reduction. Suppliers, acting as leaders, set the wholesale prices for agricultural products, and processors, as followers, determine the retail prices and the levels of carbon reduction investment based on the wholesale prices dictated by the suppliers. This decision-making process is illustrated in Figure 2. In contrast, the TS model involves both suppliers and processors investing in carbon reduction technologies, with the optimal pricing for agricultural products and strategies for emission reduction investments being the outcome of the interactive game between these parties. The decision-making dynamics are detailed in Figure 3.

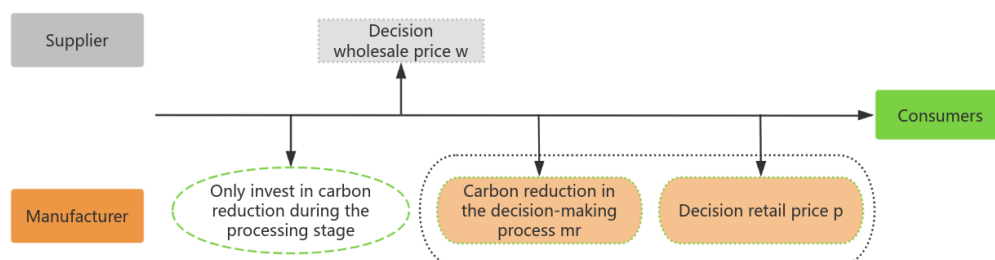


Figure 2. Decision process of Model NS.

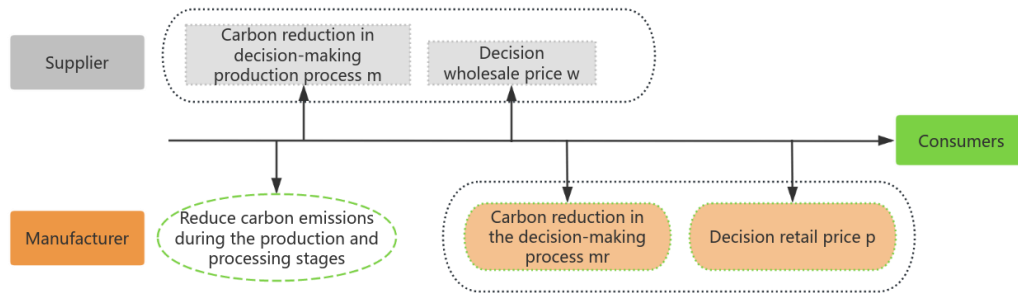


Figure 3. Decision process of Model TS.

Given the intricacies of the agricultural product supply chain, the efficacy of emission reduction measures often necessitates coordination or focus on key points within the chain, particularly where processors have high energy consumption and waste. However, focusing solely on the emission reductions of suppliers may not adequately address the overall system's carbon emission challenges. Thus, this study excludes the individual emission reduction scenarios of suppliers. By comparing the NS and TS models, we discern the differences in abatement behaviors under the individual and two-tier abatement scenarios and assess their impact on overall supply chain performance.

To examine the influence of carbon reduction labeling on the performance of agricultural product supply chains, this paper integrates the carbon footprint of agricultural products and CES into the market demand equation considering CLR and CLP. Market demand decreases when the carbon footprint exceeds the CES and increases when it falls below this threshold. Moreover, CES is calibrated to the highest average carbon emissions of comparable agricultural products; the further below this maximum average, the greater the demand. Concurrently, higher levels of CLR and CLP among consumers correspond with increased market demand. Inversely, lower recognition and preference result in decreased demand. Accordingly, this study posits that market demand for agricultural products is a function of CLR, CLP, average maximum carbon emissions, the carbon footprint, and CES.

Consumers' recognition of CES is θ_1 , and suppliers or processors reduce the carbon footprint of agricultural products through carbon reduction, thereby increasing demand. Moreover, $m_i (i = s, r)$ represents the carbon reduction level of suppliers and processors. Agricultural enterprises typically adopt two green investment approaches to reduce their carbon footprint. The first is to use cleaner energy for cultivation and planting, for instance, applying more environmentally friendly nutrients in crop production. The second is to conduct research and development (R&D) on green technologies to reduce carbon emissions during packaging, transportation, and processing. The investment cost of green technology R&D by processors (suppliers) is represented by $\frac{1}{2}\beta_1 m_r^2$ ($\frac{1}{2}\beta_2 m_s^2$), where $\beta_i (i = 1, 2)$ denotes the investment coefficient of R&D, $\beta_i > 0$. This means that the R&D cost increases rapidly with the improvement of emission reduction effect. When it reaches a certain level, emission reduction becomes extremely expensive and the effect goes weak. Similar cost functions were used in Yang and Yao [21] and Yu et al. [22]. Table 2 describes all parameters and variables of this study.

Table 2. Parameters and variables.

Parameter	Explanation
a	Initial market demand
b	Consumer price sensitivity coefficient
β_1	Cost coefficient of emission reduction efforts or investment coefficient of emission reduction technology for processors
β_2	Supplier's emission reduction effort's cost coefficient or emission reduction technology investment coefficient
l_m	Maximum carbon emissions of the product
l_0	Product's carbon emission standards (CES)
l^s	Product's carbon footprint ($s=NS, TS$)
θ_1	Consumers' recognition of carbon reduction label (CLR), $\theta_1 > 0$
θ_2	Consumers' low-carbon preference coefficient (CLP), $\theta_2 > 0$
λ_i	Initial carbon emissions of enterprise i ($i=s, r$)
P_{carbon}	Carbon trading/allowance price
Decision variables	
w	Supplier wholesale price
P	Sales price of processor products
m_i	Emission reduction level ($i=s, r$)
Functions	
π_i	The profit function of enterprise i ($i=s, r$)
π_{sc}	Supply chain's total profit function
E	Environmental benefit function
CS	Consumer surplus function
S	Social benefit function

We specify consumer demand as a function of price and two key product attributes, the carbon footprint relative to CES and the credibility of the carbon label. The underlying behavioral mechanism is twofold. On the one hand, consumers with stronger CLP derive higher utility from products whose carbon footprint falls below the CES threshold, as they perceive such purchases as contributing to environmental protection [6,10]. On the other hand, CLR determines the extent to which consumers trust and act upon the disclosed carbon information. When CLR is high, consumers are more confident that the label accurately reflects genuine emission reductions, thereby amplifying the demand response to deviations between the actual carbon footprint and the CES benchmark [12,13]. Empirical evidence from carbon-labeled agricultural products confirms that both CLP and CLR significantly affect purchase intentions and willingness to pay, with their effects being interactive rather than purely additive [9]. Accordingly, referring to Yang and Yao [21], the market demand is expressed as

$$D = a - bp + \theta_1(l_m - l_0) + \theta_2(l_0 - l^s), \quad (1)$$

where the first term represents the initial market demand, the second term represents the impact of consumers' price sensitivity on demand, the third term represents the impact of consumers' standard recognition on demand, and the fourth term represents the impact of consumers' low-carbon preferences on demand. This specification implies that the marginal effect of emission reduction on demand is increasing in both CLR (θ_1) and CLP (θ_2), with CLR exerting a stronger influence than CLP ($\theta_1 > \theta_2$). This is consistent with empirical evidence that environmentally conscious consumers respond more strongly to credible carbon information [7].

The CES parameter l_0 affects demand through two opposing channels, with their relative strength determined by θ_1 and θ_2 . The term $\theta_1(l_m - l_0)$ captures the label authority effect that a stricter standard (lower l_0) widens $(l_m - l_0)$, signaling greater regulatory ambition and enhancing labels' credibility. The term $\theta_2(l_0 - l^s)$ captures the compliance proximity effect that a stricter standard reduces $(l_0 - l^s)$, making it harder for products to qualify for the label. Given $\theta_1 > \theta_2$, the label's authority effect dominates. Stricter standards thus generate a net demand increase despite reducing the number of eligible products, because consumers value credibility more than labels' availability.

Referring to Wang et al. [19] and Fu et al. [23], the environmental benefit function is characterized as carbon abatement benefits, whose function is expressed as the product of the carbon price and emission volume. The carbon emission reduction volume equals to units of carbon abatement multiplied by the total demand [17]

$$E = p_{\text{carbon}} \times m_i \times D. \quad (2)$$

Consumer surplus describes the difference between the product price that consumers are willing to pay and the actual price when consuming a certain quantity of products [18], which is expressed as

$$CS = \frac{1}{2b} \times D^2. \quad (3)$$

Social benefits refer to the positive impact of a policy or behavior on the overall interests of society. This welfare specification follows the standard practice in supply chain management and environmental economics literature (see Zhang et al. [20] and He and Sun [18]), where social benefit is decomposed into firms' profits, consumer surplus, and environmental benefits.

$$S = \pi_{sc} + CS + E. \quad (4)$$

In addition, this study makes the following assumptions.

Assumption 1. Referring to Zhang et al. [20], the products provided by supplier s can be fully sold by Manufacturer R without stockpiling or incurring inventory costs. The standardization of costs for suppliers and processors other than emissions reduction to 0 does not affect the conclusion of the study. Adopting the standardized cost assumption enables the study to concentrate on the effects of carbon labeling.

Assumption 2. The carbon footprint is defined as the total amount of carbon dioxide or equivalent low greenhouse gas emissions directly or indirectly emitted by a specific activity (such as a product or service) [6, 24]. This paper investigates a two-echelon supply chain consisting of agricultural raw material suppliers and processors. Therefore, the sum of actual carbon emissions from these two stages is adopted to calculate the carbon footprint. Before implementing emissions reductions, the carbon

emissions of suppliers and processors are λ_m and λ_r , respectively. The processor, with or without the supplier, exerts efforts (m_r or m_s) to cut carbon emissions, resulting in their final carbon emissions. The carbon emission reduction quantity cannot exceed the initial carbon emissions, $0 \leq m_r \leq \lambda_r$, and $0 \leq m_s \leq \lambda_s$.

Assumption 3. To ensure that the demands, prices, and emission reduction levels are positive, and that optimal solutions to the objective function exist, $2b\beta_1 > \theta_2^2$ and $4b\beta_1\beta_2 - (\beta_1 + 2\beta_2)\theta_2^2$.

Assumption 4. Suppliers and processors in the agricultural supply chain are risk-neutral and pursue profit maximization.

3. Model construction

Two models are constructed for individual emissions reduction by processors (NS) and two-tier emissions reduction by suppliers and processors (TS). In the TS model, suppliers and processors are assumed to cooperate fully without coordination costs or information asymmetries. This assumption allows us to establish the theoretical upper bound of two-tier abatement performance, providing a benchmark against which independent abatement can be compared.

3.1. Construction of Model NS

The carbon footprint on the agricultural supply chain is defined as

$$l^{NS} = \lambda_s + \lambda_r - m_r. \quad (5)$$

among them, λ_s represents the initial carbon emissions of the supplier, λ_r represents the initial carbon emissions of the processor, and m_r is the carbon reduction level of the processor.

Therefore, the profit function of the processor is

$$\pi_r^{NS} = (p - w) \times D(l^{NS}) - \frac{1}{2} \beta_1 m_r^2, \quad (6)$$

where the first item represents the income of the processor, and the last item represents the emission reduction cost of the processor.

The supplier's profit function is

$$\pi_s^{NS} = w \times D(l^{NS}), \quad (7)$$

where the subscripts r and s respectively represent processors and suppliers, and the superscript NS indicates that the processors are reducing emissions separately.

According to Eqs (1), (5), (6), and (7), the optimal decision for agricultural products can be obtained using reverse induction, as shown in Theorem 1.

Theorem 1. Under carbon labeling regulations, the optimal decision for the agricultural supply chain when the processors reduce emissions separately is as follows.

The optimal wholesale price is

$$w^{NS*} = \frac{a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)}{2b}. \quad (8)$$

The optimal retail price is

$$p^{NS*} = \frac{(3b\beta_1 - \theta_2^2)[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]}{2b(2b\beta_1 - \theta_2^2)}. \quad (9)$$

The optimal carbon reduction amount is

$$m^{NS*} = \frac{\theta_2[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]}{2(2b\beta_1 - \theta_2^2)}. \quad (10)$$

The optimal demand quantity is

$$D^{NS*} = \frac{b\beta_1[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]}{2(2b\beta_1 - \theta_2^2)}. \quad (11)$$

By substituting Eqs (8,9) into Eqs (2–4,6,7), the optimal processor profit, supplier profit, environmental benefits, consumer surplus, and social benefits can be obtained as follows:

$$\pi_r^{NS*} = \frac{\beta_1[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]^2}{8(2b\beta_1 - \theta_2^2)}, \quad (12)$$

$$\pi_s^{NS*} = \frac{\beta_1[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]^2}{4(2b\beta_1 - \theta_2^2)}, \quad (13)$$

$$E^{NS*} = \frac{b\beta_1\theta_2[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]^2}{4(2b\beta_1 - \theta_2^2)^2}, \quad (14)$$

$$CS^{NS*} = \frac{b^2\beta_1^2[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]^2}{8(2b\beta_1 - \theta_2^2)^2}, \quad (15)$$

$$S^{NS*} = \frac{\beta_1(b^2\beta_1 - 3\theta_2^2 + 2b(3\beta_1 + p_{carbon}\theta_2))[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]^2}{8(2b\beta_1 - \theta_2^2)^2}. \quad (16)$$

Proof is provided in Appendix A1.

It can also be found that, when CLP falls below CLR ($\theta_2 < \theta_1$), relaxing CES (a larger l_0) reduces prices, abatement, profits, and all categories of benefits. This occurs because consumers with weak intrinsic preferences rely primarily on label credibility for purchasing decisions. Looser standards

diminish the perceived differentiation between certified and conventional products, shrinking the demand premium for abatement. Firms consequently lower both abatement investment and prices, eroding environmental gains and consumer welfare. For regulators, this result implies that tightening CES is an effective lever for enhancing market and environmental outcomes when CLP is insufficiently high.

3.2. Construction of Model TS

When suppliers and processors engage in carbon reduction activities together, the carbon footprint of agricultural products in the supply chain is defined as

$$l^{TS} = (\lambda_s - m_s) + (\lambda_r - m_r), \quad (17)$$

where the first item represents the carbon footprint of supplier s after emission reduction, and the second item represents the carbon footprint of processor r after emission reduction. Let the total emission reduction of agricultural products in Model TS be $m = m_r + m_s$.

Therefore, the profit function of the processor is

$$\pi_r^{TS} = (p - w) \times D(l^{TS}) - \frac{1}{2} \beta_1 m_r^2. \quad (18)$$

The profit function of the supplier is

$$\pi_s^{TS} = w \times D(l^{TS}) - \frac{1}{2} \beta_2 m_s^2, \quad (19)$$

where the subscripts r and s , respectively, represent processors and suppliers, and the superscript TS represents two-tier reduction.

According to Eqs (1), (17)–(19), the optimal decision for the agricultural product supply chain can be obtained using reverse induction, as shown in Theorem 2.

Theorem 2. Under carbon labeling regulations, the optimal decision for the agricultural supply chain when processors reduce emissions separately is as follows.

The optimal wholesale price is

$$w^{TS*} = \frac{\beta_2 (2b\beta_1 - \theta_2^2) [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]}{b [2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]}. \quad (20)$$

The optimal retail price is

$$p^{TS*} = \frac{\beta_2 (3b\beta_1 - \theta_2^2) [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]}{b [2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]}. \quad (21)$$

The optimal carbon reduction amount for suppliers is

$$m_s^{TS*} = \frac{\beta_1 \theta_2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]}{2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2}. \quad (22)$$

The optimal carbon reduction amount for processors is

$$m_r^{TS*} = \frac{\beta_2 \theta_2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]}{2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2}. \quad (23)$$

The optimal demand quantity is

$$D^{TS*} = \frac{b\beta_1 \beta_2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]}{2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2}. \quad (24)$$

By substituting Eqs (20–23) into Eqs (2–4, 18, 19), the optimal profit of the processor, supplier profit, environmental benefits, consumer surplus, and social benefits can be obtained as follows:

$$\pi_r^{TS*} = \frac{\beta_1 \beta_2^2 (2b\beta_1 - \theta_2^2) [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{2[2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]^2}, \quad (25)$$

$$\pi_s^{TS*} = \frac{\beta_1 \beta_2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{2[2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]}, \quad (26)$$

$$E^{TS*} = \frac{p_{carbon} b \beta_1 \beta_2 \theta_2 (\beta_1 + \beta_2) [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{[2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]^2}, \quad (27)$$

$$CS^{TS*} = \frac{b^2 \beta_1^2 \beta_2^2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{2[2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]^2}, \quad (28)$$

$$S^{TS*} = \frac{[a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{2[2\beta_2 (2b\beta_1 - \theta_2^2) - \beta_1 \theta_2^2]^2} \beta_1 \beta_2 \times [b\beta_1 \beta_2 (6+b) + 2bp_{carbon} (\beta_1 + \beta_2) \theta_2 - (\beta_1 + 3\beta_2) \theta_2^2]. \quad (29)$$

Proof is provided in Appendix A2.

When CLP falls below CLR ($\theta_2 < \theta_1$), relaxing CES similarly reduces abatement, prices, profits, and benefits. The negative effect is partially mitigated because suppliers and processors share the abatement costs, reducing each party's individual burden. Nevertheless, the overall direction remains negative, as weaker CES thresholds diminish the demand-side signal for abatement. For regulators, this finding suggests that even under two-tier abatement, maintaining stringent CES is critical for preserving the market value of abatement investments.

It can also be found that higher CLR raises wholesale prices, retail prices, abatement levels, and market demand, simultaneously improving profits, consumer surplus, environmental benefits, and social benefits through three channels. Higher CLR strengthens the demand response to abatement, raising the marginal revenue of emission reduction and incentivizing greater investment. For firms, this underscores the strategic value of participating in recognized certification programs. For managers, this implies that credible certification and transparent communication generate a virtuous

cycle of higher abatement, higher prices, and higher sales. For regulators, building consumer trust through third-party verification amplifies CES's effectiveness without altering the standards themselves. Investments in public education and label transparency generate multifaceted returns across the economic, environmental, and social dimensions.

Proposition 1. In Model TS, the impacts of CLP on supplier and processor decisions are

$$\frac{\partial w^{TS*}}{\partial \theta_2} > 0, \quad \frac{\partial p^{TS*}}{\partial \theta_2} \begin{cases} \geq 0 (l_1 \leq l_0 \leq l_m) \\ < 0 (0 \leq l_0 < l_1) \end{cases}, \quad (30)$$

$$\frac{\partial m^{TS*}}{\partial \theta_2} > 0, \quad \frac{\partial D^{TS*}}{\partial \theta_2} \begin{cases} \geq 0 (l_2 \leq l_0 \leq l_m) \\ < 0 (0 \leq l_0 < l_2) \end{cases}. \quad (31)$$

Proof is provided in Appendix A3.

Proposition 1 demonstrates that a heightened CLP correlates with an increase in carbon emissions reduction efforts. When CLP falls below a certain threshold, companies, despite enhancing their carbon reduction initiatives, may still emit more than the CES allow, which can diminish market demand. In such cases, firms may opt to lower prices to attract a greater number of consumers. Conversely, once CLP surpasses that threshold, companies ramp up their carbon reduction efforts to satisfy consumers with a stronger low-carbon stance, incurring additional expenses in the process. To recoup these costs, processors and suppliers may elect to increase product prices, thereby balancing the financial implications of their sustainability initiatives.

Proposition 2. In Model TS, the impacts of CLP on the supplier's and processor's profits, consumer surplus, and profitability are

$$\frac{\partial \pi_r^{TS*}}{\partial \theta_2} \begin{cases} \geq 0 (l_3 \leq l_0 \leq l_m) \\ < 0 (0 \leq l_0 < l_3) \end{cases}, \quad \frac{\partial \pi_s^{TS*}}{\partial \theta_2} \begin{cases} \geq 0 (l_4 \leq l_0 \leq l_m) \\ < 0 (0 \leq l_0 < l_4) \end{cases}, \quad (32)$$

$$\frac{\partial E^{TS*}}{\partial \theta_2} > 0, \quad \frac{\partial CS^{TS*}}{\partial \theta_2} \begin{cases} \geq 0 (l_5 \leq l_0 \leq l_m) \\ < 0 (0 \leq l_0 < l_5) \end{cases}, \quad \frac{\partial S^{TS*}}{\partial \theta_2} \begin{cases} \geq 0 (l_6 \leq l_0 \leq l_m) \\ < 0 (0 \leq l_0 < l_6) \end{cases}. \quad (33)$$

Proof is provided in Appendix A4.

Proposition 2 illustrates that while higher CLP unambiguously enhances the environmental benefits, its effects on profits, consumer surplus, and social benefits are nonmonotonic. Below a critical threshold, firms bear higher abatement costs but cannot fully pass them through due to insufficient willingness to pay, creating a cost–price squeeze that reduces profits and consumer surplus. Above the threshold, robust consumer demand allows premium pricing that more than offsets abatement costs, driving improvements across all metrics. For firms, this highlights a tipping point in preference evolution. Early movers may face transitional losses, but sustained investments yield disproportionate gains as preferences mature. For regulators, policies that accelerate CLP's growth, such as public awareness campaigns, can help supply chains cross this tipping point more quickly.

4. Comparative analysis

The preceding sections derived the optimal solutions for both the NS and TS models, examining the influence of CLR and CLP on the supply chain's economic and environmental performance under the CES policy. This section delves into the analysis and discussion of the outcomes from both the NS and TS models.

First, we compare the optimal pricing, carbon reduction level, and market demand between the NS and TS models, probing how the interests of businesses, consumers, and society evolve as a result.

Proposition 3. In the TS model, there is a notable increase in product prices, emission reduction efforts, and market demand when compared with the NS model.

Let $\Delta w = w^{TS*} - w^{NS*}$, $\Delta p = p^{TS*} - p^{NS*}$, $\Delta m = m_r^{TS*} + m_s^{TS*} - m^{NS*}$, and $\Delta D = D^{TS*} - D^{NS*}$ to calculate the result, yielding

$$(i) \quad w^{TS*} > w^{NS*}, \quad p^{TS*} > p^{NS*}, \quad (34)$$

$$(ii) \quad m_r^{TS*} + m_s^{TS*} > m^{NS*}, \quad D^{TS*} > D^{NS*}. \quad (35)$$

Proof is provided in Appendix A5.

Proposition 3 suggests that greater abatement in the supply chain can attract more consumers and expand market demand. However, the heightened costs associated with carbon reduction necessitate an increase in product prices by suppliers, resulting in higher retail prices for processors. This, in turn, can dampen market demand and adversely impact the supply chain's efficiency. Consequently, supply chain participants must innovate in carbon reduction technologies and management approaches to mitigate these costs.

Second, the differential impacts of CLR and CLP across the two models are discussed.

Proposition 4.

$$\frac{\partial \Delta m}{\partial \theta_1} > 0, \quad \frac{\partial \Delta D}{\partial \theta_1} > 0. \quad (36)$$

Proof is provided in Appendix A6.

Proposition 4 indicates that the abatement, price, and demand advantages of two-tier abatement over independent abatement all widen monotonically with CLR. This monotonic amplification occurs because higher label recognition increases the market reward for every unit of abatement, and this reward is captured more fully in the TS model where abatement is larger. In other words, CLR acts as a "multiplier" that disproportionately benefits the model with higher baseline abatement. For firms, this implies that investments in two-tier abatement become increasingly valuable as consumers' trust in the labeling system grows, suggesting that first-mover advantages in two-tier abatement can be substantial in markets with high label credibility.

Proposition 5.

$$\frac{\partial \Delta m}{\partial \theta_2} > 0, \quad \frac{\partial \Delta D}{\partial \theta_2} > 0. \quad (37)$$

Proof is provided in Appendix A7.

Proposition 5 reveals a more complex pattern for CLP. While the abatement gap between TS and NS widens monotonically with CLP, the demand gap first narrows and then widens. The initial narrowing occurs because when CLP is low but rising, firms in both models increase abatement, but the NS model's abatement response is more price-sensitive, leading to relatively larger demand gains at the margin. As CLP continues to rise, the TS model's superior abatement capacity generates increasingly differentiated products that command a growing demand premium, eventually causing the demand gap to widen again. For managers, this nonmonotonicity implies that the competitive advantage of two-tier abatement over independent abatement is not constant, and the optimal strategy choice may depend on the current level of consumers' environmental awareness. For regulators, the finding suggests that the effectiveness of policies promoting two-tier abatement may be amplified or attenuated, depending on the development stage of consumers' preference.

Proposition 6. In the TS model, members' profits, environmental benefits, consumer surplus, and social benefits are all greater than those in the NS model.

Let $\Delta\pi_r = \pi_r^{TS*} - \pi_r^{NS*}$, $\Delta\pi_s = \pi_s^{TS*} - \pi_s^{NS*}$, $\Delta E = E^{TS*} - E^{NS*}$, $\Delta CS = CS^{TS*} - CS^{NS*}$, and $\Delta S = S^{TS*} - S^{NS*}$, we get

$$(i) \quad \pi_r^{TS*} > \pi_r^{NS*}, \quad \pi_s^{TS*} > \pi_s^{NS*}, \quad (38)$$

$$(ii) \quad E^{TS*} > E^{NS*}, \quad CS^{TS*} > CS^{NS*}, \quad S^{TS*} > S^{NS*}. \quad (39)$$

Proof is provided in Appendix A8.

Proposition 6 demonstrates that the collective rise in prices, reductions in emissions, and growth in demand contribute to the profitability of supply chain members. The adoption of environmentally friendly production practices augments the environmental benefits by curtailing carbon emissions. While price increases might impinge on consumer surplus, the concurrent surge in demand indicates a positive consumer reception for the product. For firms, two-tier abatement is not merely regulatory compliance but a source of competitive advantage. For regulators, facilitating vertical cooperation generates Pareto improvements across all dimensions and should be a policy priority.

Proposition 7. The impacts of CLR on $\Delta\pi_i$, ΔE , ΔCS , and ΔS are

$$\frac{\partial \Delta\pi_s}{\partial \theta_1} > 0, \frac{\partial \Delta\pi_r}{\partial \theta_1} > 0, \frac{\partial \Delta E}{\partial \theta_1} > 0, \frac{\partial \Delta CS}{\partial \theta_1} < 0, \frac{\partial \Delta S}{\partial \theta_1} < 0. \quad (40)$$

Proof is provided in Appendix A9.

Proposition 7 shows that as CLR increases, the gaps in profits, environmental benefits, consumer surplus, and social benefits between TS and NS all widen monotonically. Higher label recognition magnifies the demand-side reward for abatement, and because the TS model generates more abatement, it captures a disproportionately larger share of this expanded reward. For firms, this implies that the relative benefit of engaging in two-tier abatement grows as consumers become more sophisticated in interpreting carbon labels. For regulators, the finding suggests that efforts to improve labels' transparency and consumer education have the added benefit of making two-tier abatement strategies more attractive relative to independent ones.

Proposition 8. The impacts of CLP on $\Delta\pi_i$, ΔE , ΔCS , and ΔS are

$$\frac{\partial \Delta \pi_s}{\partial \theta_2} > 0, \frac{\partial \Delta \pi_r}{\partial \theta_2} > 0, \frac{\partial \Delta E}{\partial \theta_2} > 0, \frac{\partial \Delta CS}{\partial \theta_2} > 0, \frac{\partial \Delta S}{\partial \theta_2} > 0. \quad (41)$$

Proof is provided in Appendix A10.

Proposition 8 indicates that the gaps in profits and environmental benefits widen monotonically with CLP. By contrast, the gaps in consumer surplus and social benefits follow a U-shaped trajectory. This initial narrowing occurs because the TS model's higher prices suppress surplus growth at low to moderate CLP levels, whereas the NS model's lower prices allow consumers to retain more surplus despite inferior abatement. As CLP rises further, the TS model's demand expansion outweighs its price effect, allowing it to surpass the NS model. For managers, this U-shaped pattern suggests that two-tier abatement may face consumer resistance in markets with intermediate environmental awareness.

5. Numerical analysis and discussion

We draw on the operations of Bright Food (Group) Co., Ltd., one of China's largest agricultural and food conglomerates. Bright Food has an extensive fresh produce supply chain, including radish cultivation and processing, and has publicly committed to carbon reduction targets under China's "dual carbon" goals. The company has implemented various green practices, such as optimizing fertilizer use, improving cold-chain logistics efficiency, and adopting renewable energy in processing facilities. However, like many agricultural enterprises, Bright Food faces challenges in coordinating emission reduction efforts between its upstream suppliers (contracted farming cooperatives) and its downstream processing divisions, making the NS versus TS strategy comparison highly relevant to its operational context.

With the segmentation of consumer groups in the market, radishes are divided into four levels according to size, weight, and appearance: Premium, average, small, and defective. This requires supply chain members to apply technology or manpower labor to complete the cultivation, planting, picking, cleaning, sorting, packaging, and sales processes.

In the radish supply chain, suppliers are responsible for the planting, cultivation, and harvesting of radishes, among which, the mechanization of planting and harvesting processes and the use of fertilizers and pesticides result in significant carbon emissions. The processor is responsible for cleaning, sorting, packaging, and other processing of radishes, which also generates a large amount of carbon emissions. Referring to Lopes et al. [25], the maximum carbon emissions generated from the production and processing of each ton of radish in the entire radish supply chain are 2000 kg CO₂eq (carbon dioxide equivalents), the average emissions from the suppliers are 700 kg CO₂eq/t, and the average emissions from the processors are 800 kg CO₂eq/t. To capture different regulatory stringency levels, we compare two CES scenarios: Strict CES ($l_0 = 10$ kg CO₂eq/t) and relaxed CES ($l_0 = 1000$ kg CO₂eq/t). We assume that the green investment cost coefficient for suppliers and processors is 1, CLR (θ_1) is 0.8, and CLP (θ_2) is 0.4.

5.1. Analysis of the impact of CLR

CLR signifies the degree to which consumers acknowledge and trust the information provided by carbon reduction labels, subsequently influencing their purchasing decisions. The CLR level is intricately linked to the regulatory authority behind the CES.

When the government spearheads the development of CES, it often enjoys high authority and credibility, leading to greater consumer recognition. For instance, the European Union's CES, which

is crafted by the European Commission, is widely regarded by consumers as highly credible. In contrast, when industries self-regulate and establish CES, these standards may gain traction within the industry but may not resonate as strongly with consumers. Some industry associations might set CES, yet these might not garner extensive consumer recognition. Furthermore, when firms autonomously set CES, there is a possibility that these standards prioritize the firms' interests, potentially resulting in the lowest consumer recognition. Some firms might lower their carbon emission benchmarks to cut costs, which could fall short of consumers' expectations.

To investigate the impact of CLR (θ_1) on the supply chain's performance and efficiency under relaxed CES and strict CES, we compared the growth of two models with CLR (θ_1) under two different criteria. NSL denotes the scenario of the NS model under relaxed standards, NSh signifies the NS model under strict standards, TSL indicates the TS model under relaxed standards, and TSh represents the TS model under stringent standards.

(1) Impact of CLR on carbon emission reductions

As depicted in Figure 4, an increase in CLR (θ_1) is associated with a higher level of emission reduction across the supply chain. Notably, two-tier emission reduction consistently outperforms individual efforts in terms of carbon reduction. Regardless of whether the NS or TS model is applied, stricter standards consistently yield higher emission reductions compared with more lenient ones.

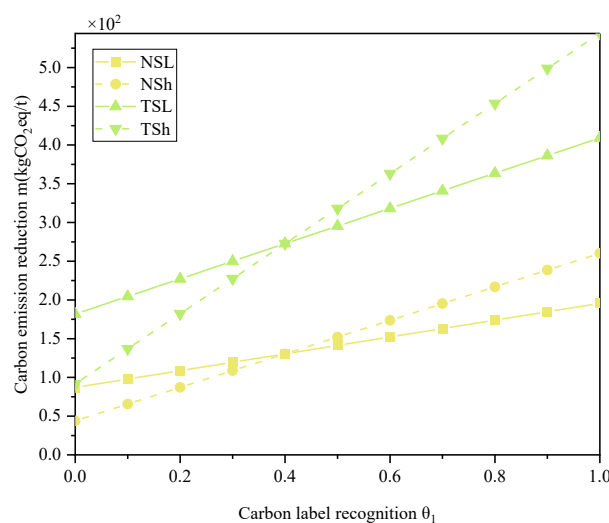


Figure 4. Impacts of CLR on carbon emission reductions under two CES and two models.

Observation 1. Elevated CLR and the implementation of two-tier emission reduction strategies can markedly enhance the efficacy of carbon reduction. This underscores the importance of heightened consumer engagement and the adoption of stringent emission reduction standards in achieving more effective carbon reduction goals.

(2) Impact of CLR on the processor's profits

Figure 5 illustrates that as CLR (θ_1) increases, so does the processor's profit, with two-tier emission reduction strategies consistently yielding higher profits than individual efforts. At higher

CLR levels, processors reap greater profits under strict standards compared with those under lenient standards, irrespective of whether the NS or TS model is in place.

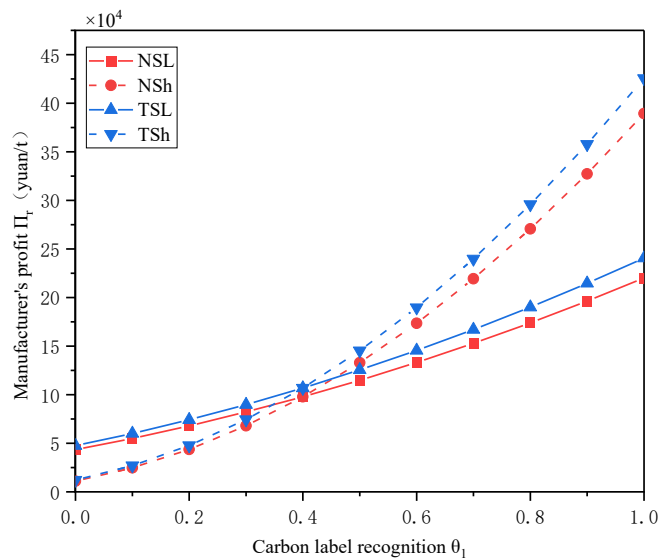


Figure 5. Impacts of CLR on the processor's profits under two CES and two models.

Observation 2. Elevated CLR levels have spurred market demand for these products. Stringent standards ensure the precision of carbon labeling, rendering low-carbon products from processors more competitive. By offering products that adhere to these rigorous standards, manufacturers can command higher market premiums, thus boosting profits. This approach not only distinguishes them in a competitive market but also widens profit margins.

(3) Impact of CLR on the supplier's profits

It is evident in Figure 6 that as CLR (θ_l) rises, so too does the supplier's profit, with two-tier emission reduction efforts consistently outperforming individual reduction models in terms of profitability. At high CLR levels, suppliers under strict standards enjoy greater profits than their counterparts under loose standards, regardless of whether the NS or TS model is applied. This is attributable to the fact that high CLR has bolstered market demand for eco-friendly products. Stringent standards ensure the precision and credibility of carbon labeling, positioning suppliers to command a premium for their low-carbon products, thus enhancing their competitiveness in the market. Consequently, suppliers can elevate product prices to align with market demand, significantly amplifying their profits.

Observation 3. Amplifying CLR and adhering to stringent emission reduction standards will not only escalate suppliers' profitability but also motivate broader participation in environmental initiatives, fostering the sustainable progression of the entire supply chain.

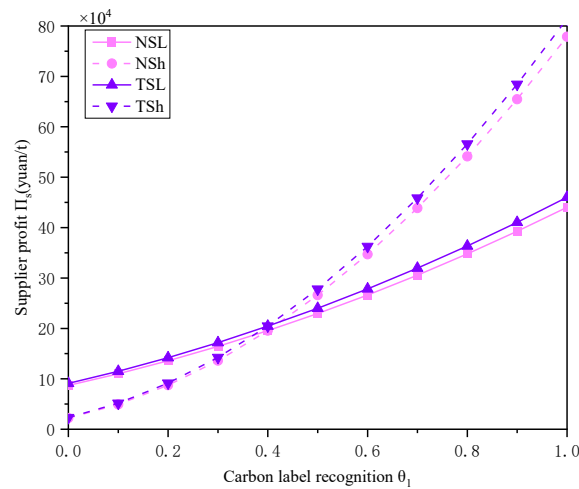


Figure 6. Impacts of CLR on the supplier's profits under two CES and two models.

(4) Impact of CLR on environmental benefits

Figure 7 clearly shows that as CLR (θ_1) increases, so do the environmental benefits. Notably, the two-tier emission reduction model under CES consistently delivers higher environmental benefits compared with the individual emission reduction model. When CLR is high, the environmental benefits under strict standards surpass those under loose standards, regardless of whether the NS or TS model is in effect. This is because high CLR has spurred market demand for low-carbon products. Stringent standards ensure the accuracy of carbon labeling, bolstering the market appeal of low-carbon products and encouraging companies to invest more in emission reduction technologies. This synergy fosters the adoption of more effective emission reduction strategies, leading to a marked enhancement in overall environmental benefits.

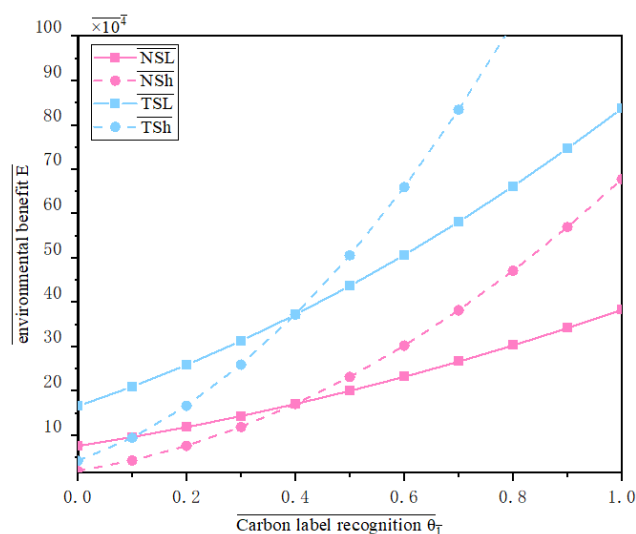


Figure 7. Impacts of CLR on environmental benefits under two CES and two models.

Observation 4. Enhancing CLR and enforcing stringent emission reduction standards can significantly amplify the efficacy of environmental conservation efforts, underscoring the necessity for comprehensive measures and a strong sense of responsibility in realizing environmental objectives.

(5) Impact of CLR on social benefits

Figure 8 demonstrates that as CLR (θ_l) increases, so too do social benefits. Consistently, the two-tier emission reduction model under CES outperforms the individual emission reduction model in terms of social benefits. At high CLR levels, strict standards lead to greater social benefits compared with relaxed standards, irrespective of whether the NS or TS model is applied. High CLR stimulates market demand for eco-friendly products. Stringent standards ensure the precision and reliability of carbon labels, effectively highlighting the environmental advantages of low-carbon products. This dynamic encourages enterprises to adopt more potent emission reduction strategies, resulting in larger carbon emission reductions and an increase in overall social benefits.

Observation 5. Strengthening CLR and implementing stringent emission reduction standards can markedly enhance social benefits, indicating that these initiatives are instrumental in optimizing societal welfare.

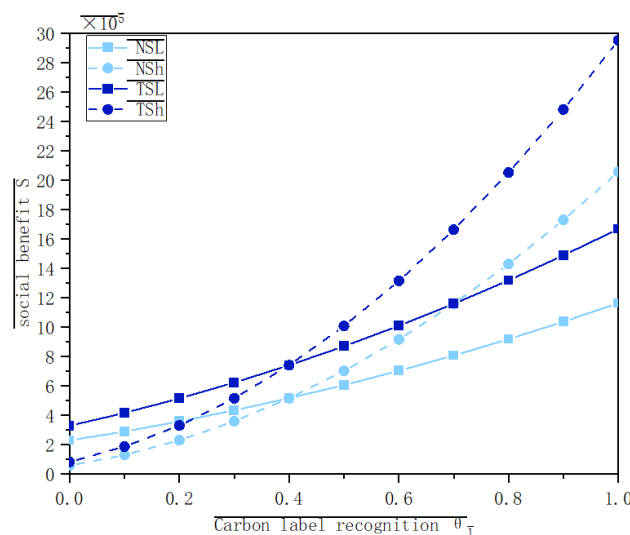


Figure 8. Impacts of CLR on social benefits under two CES and two models.

(6) Impact of CLR on consumer surplus

Figure 9 indicates that as CLR (θ_l) rises, so does consumer surplus. Similarly, under the CES, the two-tier emission reduction model consistently yields higher consumer surplus compared with the individual emission reduction model. When CLR is elevated, strict standards result in greater consumer surplus across both the NS and TS models than lenient standards. This is because consumers perceive their purchasing behavior as more impactful for environmental conservation, which enhances their sense of responsibility and drives their preference for low-carbon products. This willingness to pay a premium for eco-friendly options, in turn, boosts their surplus.

Observation 6. Enhancing CLR and implementing stringent emission reduction standards not only elevates consumers' economic welfare but also augments overall consumer surplus by fostering a heightened level of environmental protection.

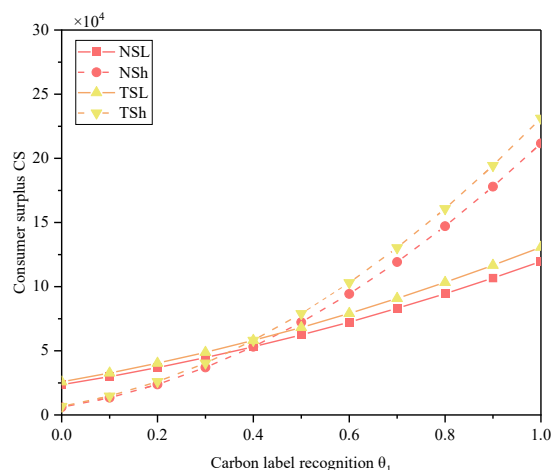


Figure 9. Impacts of CLR on consumer surplus under two CES and two models.

5.2. Analysis of the impact of CLP

CLP also affects business decision-making, as it represents the green level of the marketing environment. A larger CLP indicates that consumers have higher environmental awareness and are more willing to purchase green products.

(1) Impact of CLP on carbon emission reductions

Figure 10 illustrates that under stringent CES (l_0), the carbon reduction level for both the NS and TS models is higher when CLP (θ_2) is low, and is lower when CLP is high compared with that under relaxed CES. As CLP increases, the carbon reduction levels for both models gradually rise, with two-tier emission reduction efforts surpassing individual efforts. High CLP motivates consumers to seek out low-carbon products, stimulating market demand. Relaxed standards allow a broader range of products to bear the low-carbon label, expanding the market's low-carbon offerings. Consequently, companies, in response to robust market demand, are more inclined to intensify their emission reduction initiatives, bolster the market share of low-carbon products, and achieve a broader impact on carbon reduction.

Observation 7. Elevating CLP and implementing two-tier emission reduction strategies can significantly boost carbon emission reduction levels and optimize environmental outcomes across varying degrees of stringency in the standards.

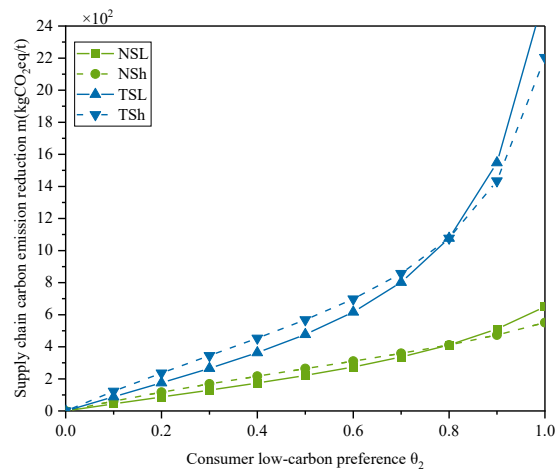


Figure 10. Impacts of CLP on carbon reduction under two CES and models.

(2) Impact of CLP on market demand

Figure 11 demonstrates that when CLP (θ_2) is low, the demand with both the NS and TS models under stringent CES (l_0) exceeds that under relaxed CES. Conversely, when CLP is high, demand under stringent CES is lower than under relaxed CES. For both the NS and TS models, as CLP increases, demand initially declines before subsequently rising. This is because a high CLP prompts consumers to actively seek out low-carbon products. Relaxed standards allow a greater number of products to be labeled as low-carbon, thereby increasing the diversity and availability of such products in the market. These standards lower the barrier to entry for products, facilitating easier market access for businesses and, in turn, satisfying the robust consumer demand for low-carbon products, which enhances the market demand for them overall.

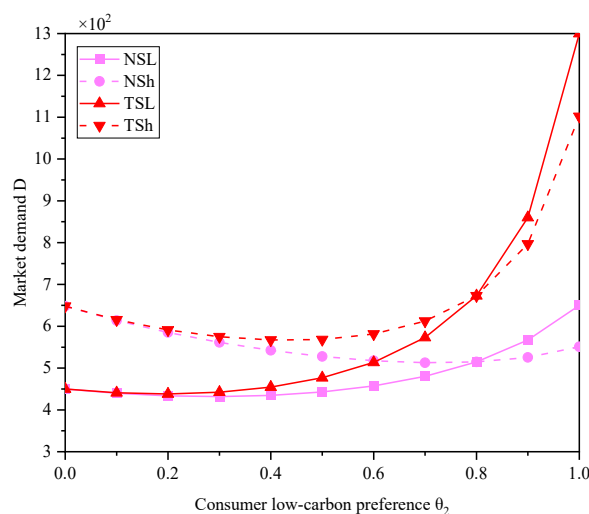


Figure 11. Impacts of CLP on demand under two types of CES and two models.

Observation 8. When CLP is substantial, the combination with relaxed standards boosts product demand more effectively. This suggests that the influence of carbon emission regulation changes on demand is intricate, with varying CES yielding different demand outcomes at different CLP levels. This complexity necessitates a comprehensive approach to optimize policy effectiveness.

(3) Impact of CLP on the processor's profits

Figure 12 indicates that when CLP (θ_2) is low, the profits for both the NS and TS models under stringent CES (l_0) are higher than under relaxed CES. However, when CLP is high, profits under stringent CES are lower compared with relaxed CES. Within the TS model, the processor's profits initially decrease and then increase with rising CLP. In contrast, in the NS model, under strict CES, the processor's profits decline continuously as CLP increases. Under relaxed CES, the processor's profits initially decrease and then increase with the rise in CLP. This is because a high CLP has intensified market demand for low-carbon products. Relaxed standards allow more products to achieve low-carbon certification, boosting the market supply of such products. This enables processors to secure certification at a lower cost, satisfy a broader market demand, and thus increase sales volume and profits. Reducing the certification threshold also allows manufacturers to adapt more nimbly to market conditions, enhancing overall profitability.

Observation 9. When CLP is significant, combining it with relaxed standards can more effectively increase processors' profits. This suggests that the interplay between CLP and CES significantly affects processors' profitability, and strategic adjustments are necessary depending on the specific contexts to maximize economic benefits.

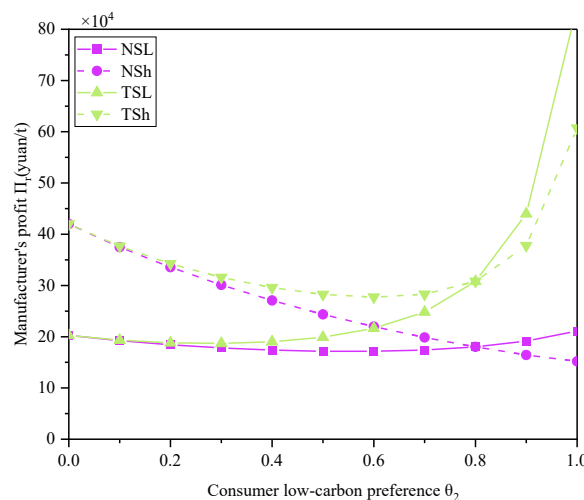


Figure 12. Impacts of CLP on the processor's profits under two CES and two models.

(4) Impact of CLP on the supplier's profits

Figure 13 illustrates that when CLP (θ_2) is low, the supplier's profits for both the NS and TS models under stringent CES (l_0) exceed those under relaxed CES. Conversely, when CLP is high, the supplier's profits under stringent CES are lower than under relaxed CES. In the TS model, as CLP increases, the supplier's profits initially dip before rising. In the NS model, under strict CES, the supplier's profits steadily decline with the rise in CLP. Under relaxed CES, the supplier's profits

initially decrease then increase as CLP rises. This is because a high CLP motivates consumers to opt for low-carbon products. Relaxed standards reduce the barriers to obtaining low-carbon certification, enabling more products to be marketed as low-carbon and broadening market opportunities for suppliers. This allows suppliers to secure certification at a lower cost, satisfy consumer demand, boost sales, and enhance profits. Additionally, the increased availability of low-carbon products can further stimulate market demand and expand suppliers' profit margins.

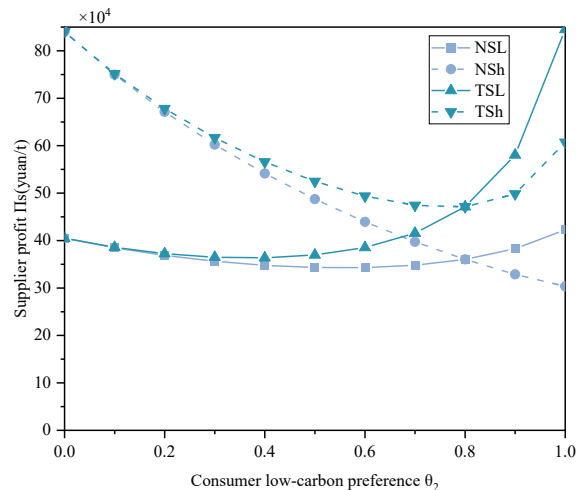


Figure 13. Impacts of CLP on the supplier's profits under two types of CES and two models.

Observation 10. When CLP is substantial, aligning it with relaxed standards can more effectively amplify the supplier's profits. This suggests that the influence of CLP and CES changes on suppliers' profitability is intricate, necessitating strategic adjustments depending on the specific context to optimize economic benefits.

(5) Impact of CLP on environmental benefits

Figure 14 demonstrates that when CLP (θ_2) is low, the environmental benefits for both the NS and TS models under stringent CES (l_0) are greater than those under relaxed CES. However, when CLP is high, the environmental benefits under stringent CES are lower than under relaxed CES. As CLP increases, environmental benefits gradually improve, with two-tier emission reductions consistently yielding higher benefits than individual efforts. This is because a high CLP has driven up market demand for low-carbon products. Relaxed standards reduce the barriers to low-carbon certification, allowing more products to be marketed with low-carbon labels and expanding the market's low-carbon offerings. This combination of policies increases the supply of low-carbon products, encouraging companies to widely adopt environmental protection measures, thereby reducing overall carbon emissions. The proliferation of low-carbon products in the market boosts overall environmental benefits and contributed to achieving broader carbon reduction goals.

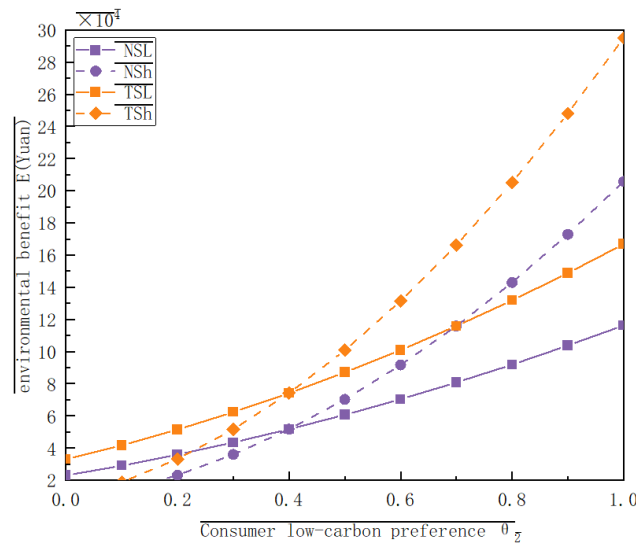


Figure 14. Impacts of CLP on environmental benefits under two types of CES and two models.

Observation 11. When CLP is significant, combining it with relaxed standards can more effectively enhance environmental benefits. This suggests that increasing CLP and implementing two-tier emission reduction strategies can substantially improve environmental outcomes, leading to better environmental protection across varying levels of standard strictness.

(6) Impact of CLP on consumer surplus

Figure 15 illustrates that at low CLP (θ_2), the consumer surplus of the NS and TS models under strict CES (l_0) surpass those under relaxed standards. Conversely, at high CLP, these benefits are subdued compared with the relaxed CES scenario. As CLP rises, consumer surplus incrementally improves, with two-tier emission reductions consistently outperforming individual efforts. This is attributable to the heightened demand for low-carbon products at elevated CLP, which incentivizes a robust market for such goods. Loose CES reduces the certification costs for low-carbon products, facilitating a broader range of goods to earn low-carbon certification at more accessible prices. This expansion in supply meets the growing consumer preference for low-carbon options, allowing for more affordable purchases that align with eco-friendly values. Consequently, consumer satisfaction and consumer surplus are enhanced.

Observation 12. A higher CLP can more effectively boost consumer surplus when paired with loose standards. This suggests that a strategic increase in CLP, coupled with two-tier reduction initiatives, can markedly amplify the efficiency of environmental conservation and optimize environmental benefits across varying CES.

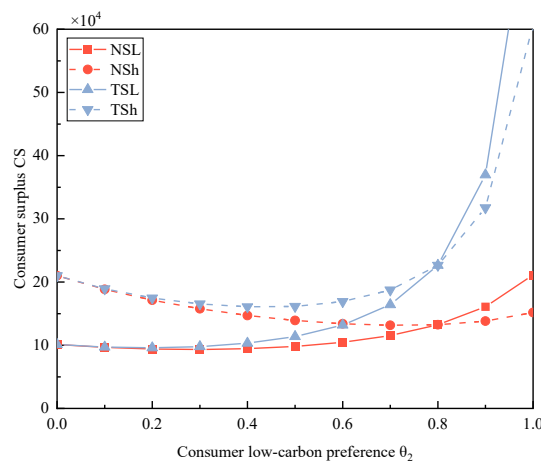


Figure 15. Impacts of CLP on consumer surplus under two types of CES and two models.

(7) Impact of CLP on social benefits

Figure 16 delineates a nuanced relationship between CLP (θ_2) and CES (l_0) on the social benefits of the NS and TS models. At lower CLP, both models yield greater social benefits under strict CES than under relaxed CES. However, at higher CLP, the social benefits are comparatively less than under strict CES. Within the TS model, social benefits initially decline and then rebound with increasing CLP under strict CES, while they show a consistent upward trend under relaxed CES. The NS model mirrors this pattern irrespective of CES's stringency.

The heightened CLP stimulates demand for low-carbon products, and the relaxed CES lowers the certification barrier, thereby broadening the market reach of low-carbon products. This expansion enables more firms to manufacture low-carbon products at reduced costs, propelling the market towards environmental sustainability. This shift not only mitigates carbon emissions but also fosters the adoption of green technologies, leading to environmental enhancement and increased social welfare and, consequently, elevated social benefits.

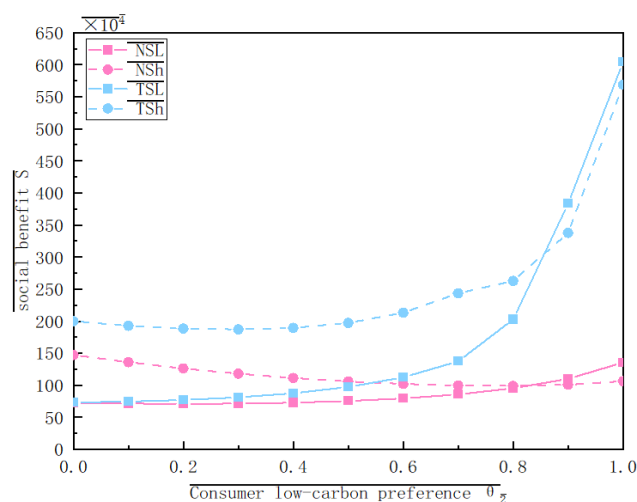


Figure 16. Impacts of CLP on social benefits under two types of CES and two models.

Observation 13. The response of social benefits to CLP varies with CES's stringency and the reduction model. Under strict CES, social benefits exhibit a U-shaped trend in the TS model; under relaxed CES, they increase monotonically. In the NS model, a U-shaped trend persists irrespective of CES's stringency. Thus, no single CES level universally maximizes the social benefits.

5.3. Comprehensive impact of CLR and CLP on social benefits under different CES

As shown in Figure 17, in the two-tier emission reduction mode, strict CES are generally more beneficial to society than loose CES, but it still depends on CLP and CLR. When $CLR(\theta_1) > CLP(\theta_2)$, the social benefits under strict CES (l_0) are always higher than those under relaxed CES. When $CLR < CLP$, two situations will occur; when CLP is too high, the social benefits under strict CES are higher than those under relaxed CES, and when CLP is high, the social benefits under strict CES are lower than those under relaxed CES.

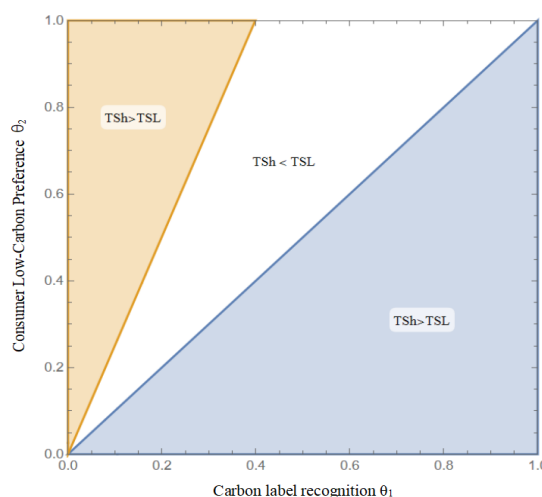


Figure 17. Comprehensive impacts of CLP and CLR on social benefits under two types of CES.

Observation 14. In the TS model, strict carbon reduction labeling standards are usually more beneficial to social benefits, and when the CLR is higher than the CLP, the social benefits under strict standards are better than those under lax standards; while the situation is complicated when the CLR is lower than the CLP, which suggests that a combination of consumer low-carbon preferences and acceptance needs to be taken into account to optimize the social benefits.

6. Conclusions and policy recommendations

This study investigates the carbon reduction issues between suppliers and processors in the context of carbon labeling. A Stackelberg game model is established to explore the impact of CES on the profitability and efficiency of two decision-makers, suppliers and processors. The study elucidates how firms simultaneously pursue sustainability and profitability by determining optimal abatement levels and the resulting environmental and social benefits. An analysis is conducted with these decision-makers under both individual and two-tier emission reductions. We added CES to the

proposed model and analyzed the impact of different CES on improving supply chain performance and social and environmental benefits. By comparing two scenarios, we draw several conclusions.

Our study reveals that stringent CES, regardless of whether companies opt for individual or collective emission reduction strategies, can lead to increased carbon reduction in the supply chain when CLR is high. This approach not only boosts corporate earnings and expands social and environmental benefits but also enhances consumer surplus. High CLR, in conjunction with strict CES, translates into greater revenue and more significant environmental and social advantages for businesses compared with lenient CES.

Furthermore, under high CLR, strict CES widens the efficiency gap between two-tier and individual emission reductions, with the former showing superior results. As CLR rises, the divergence in emission reduction levels, profits, and environmental benefits between two-tier and individual efforts becomes more pronounced, with two-tier reduction strategies outperforming individual ones.

Third, an increase in CLP incentivizes supply chain actors to achieve more ambitious emission reduction targets and bolsters profitability across the board. Under strict CES, a higher CLP drives up the supply chain's overall carbon reduction and environmental benefits. The dynamics of corporate profits, consumer surplus, and social benefits are contingent upon the emission reduction approach. Two-tier emission reduction under strict CES leads to an initial decline followed by an increase in profits and social benefits with rising CLP, while consumer surplus decreases. Conversely, individual emission reduction under strict CES results in a decline in profits and social benefits with increasing CLP, with consumer surplus experiencing an initial drop followed by an uptick.

Fourth, we discovered that the extent to which strict CES exacerbates the impact of emission reduction, profits, environmental benefits, social benefits, and consumer surplus gaps between the two models hinges on CLP. When CLP falls below a certain threshold, strict CES intensifies the disparities driven by CLP compared to relaxed CES.

Fifth, the research underscores the pivotal role of suppliers and processors in carbon emission reduction efforts. Their green initiatives can attract eco-conscious consumers, facilitate better emission reductions across the supply chain, and secure higher profits for all stakeholders. Additionally, these efforts contribute to improved environmental benefits, consumer surplus, and social welfare.

Lastly, we examined the synergistic effects of CLP and CLR on individual and two-tier emission reductions under both strict and relaxed CES conditions. Our case studies indicate that individual emission reduction models under strict standards are not inherently inferior to two-tier reduction models under relaxed standards, contingent upon CLP and CLR. Therefore, when selecting an emission reduction strategy, companies should consider the trifecta of CES, CLR, and CLP to make informed decisions.

This study offers strategic guidance for stakeholders within the low-carbon agricultural product supply chain. For policymakers, strategically increasing CLR under stringent CES can significantly bolster firms' abatement efforts, yielding substantial environmental and social dividends. Beyond mere standard enforcement, CLP emerges as a pivotal determinant of CES's supply chain impact. Elevated CLP levels drive up corporate emission reduction initiatives and enhance environmental outcomes, but they may simultaneously compromise corporate profitability and social benefits. Thus, standard developers must exercise prudence when rolling out regulations, recognizing that varying CES stringencies can have disparate effects on business earnings and societal advantages. Specifically, when CLP is high, adopting less restrictive CES can maximize corporate profits and social benefits.

For enterprises, the study underscores that two-tier emission reduction initiatives are not only beneficial but also essential. Suppliers should heed government directives, collaborate with processors

to minimize emissions, fulfill their social responsibilities, and adopt a holistic approach to abatement and eco-friendly production. The collective betterment of the environment necessitates concerted efforts from all quarters, with two-tier emission reduction emerging as a potent strategy for achieving mutually advantageous outcomes.

For consumers, fostering a heightened awareness of low-carbon practices can stimulate carbon reduction efforts and enhance environmental benefits. Under relaxed CES, consumers are encouraged to ramp up their low-carbon preferences to secure a larger consumer surplus and amplify the social benefits. When supply chain actors embrace two-tier emission reduction strategies, consumers who align their preferences accordingly can reap higher consumer surpluses and benefits, particularly when compared with scenarios where individual emission reductions are pursued.

Several limitations warrant acknowledgment. First, our finding that the TS model outperforms the NS model is conditional rather than universal. This result holds under specific assumptions, particularly $\theta_1 > \theta_2$ (CLR dominates CLP), the absence of coordination costs, and symmetric cost structures. If these conditions are relaxed, for instance, when $\theta_1 < \theta_2$ or when abatement costs are highly asymmetric, the advantage of the TS model may diminish or even reverse. Second, our TS model does not include the coordination costs, bargaining frictions, and information asymmetries that are common in practice. The superior performance of two-tier abatement should thus be interpreted as the theoretical upper bound under ideal conditions. Future research could extend our model by incorporating these factors through Nash bargaining, principal–agent frameworks, or dynamic games. Empirical studies might also examine the magnitude of coordination costs and their moderating effects across different agricultural supply chain contexts.

Author contributions

Huan Zhang: Conceptualization, methodology, writing—Original draft preparation, funding acquisition; Shucui He: Software, data curation, visualization, writing—original draft; Jianli Jiang: Funding acquisition; writing—reviewing and editing, investigation; Xiaoyu Ju: Validation, visualization, supervision.

Data availability

Data will be made available on request.

Use of generative-AI tools declaration

The authors declared that no generative AI tools were used in the preparation of this manuscript. All content is the original work of the authors.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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