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Government Subsidy Strategies in Blockchain-Enabled Dual-Channel Green Supply Chains

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ABSTRACT

To promote the high-quality development of green supply chains, this study considers government investment subsidies for blockchain technology and incorporates blockchain influence and blockchain service commission mechanism into the analysis. Particularly in the textile industry, the traceability of green fibers and carbon footprints has become a core concern for supply chain management. A Stackelberg game model is developed in which the government acts as the leader, followed by a manufacturer and a retailer, to examine the impacts of different government subsidy strategies. The results show that green technology subsidies can effectively enhance product greenness and market demand, increase the profits of supply chain members, and improve overall social welfare. Further analysis indicates that, under the same total government subsidy expenditure, green technology subsidies are more effective in improving product greenness, environmental benefits, and social welfare, whereas price subsidies are more conducive to expanding sales volume and increasing the profits of supply chain members as well as consumer surplus.

KEYWORDS
blockchain, government subsidy strategy, textile supply chain, social welfare, dual channels

INTRODUCTION

The promotion of green and low-carbon economic and social development is a key aspect of achieving high-quality development. Green development is an inevitable choice to overcome resource and environmental bottlenecks, transform development methods, and achieve sustainable and high-quality development[1]. As a key consumer goods industry, the textile industry faces significant pressure to reduce carbon emissions and transition toward green manufacturing. Green supply chain management aims to maintain high efficiency while minimizing the negative environmental impact[2]. However, related enterprises in the green supply chain often face increased costs in the process of implementing low-carbon emission reductions, green optimization, and technological innovation. These costs do not immediately provide competitive advantages or profitability. Government subsidies are effective in incentivizing enterprises to reform and innovate, thereby guiding the development of green supply chains[3].

Furthermore, consumers often worry about the authenticity and quality of products when shopping online[4]. To address this issue, blockchain technology is applied in e-commerce for anti-counterfeiting traceability, leading to innovations in the e-commerce field. Blockchain enables the construction of a transparent and traceable supply chain system that tracks the entire product flow from production to sales. This significantly enhances the transparency and reliability of the supply chain and effectively addresses information asymmetry and trust issues inherent in traditional supply chain models[5]. Blockchain can also address consumer trust issues when purchasing green, low-carbon products[6]. Therefore, studying government subsidy strategies for green dual-channel supply chains based on blockchain technology is of great significance. For instance, in the textile market, consumers often demand verifiable evidence regarding the use of recycled fibers or organic cotton. Therefore, integrating blockchain into the textile supply chain can effectively address these transparency concerns.

Different government subsidy decisions will impact the decisions of supply chain members and social welfare to varying degrees. Enterprises primarily provide two types of subsidies to supply chain members: green technology subsidies and sales volume subsidies for green products. The former targets green technology developers (i.e., suppliers) and is a behavioral subsidy, while the latter is a result-based subsidy for green products already sold to consumers through online and offline channels. Bigerna[7] finds that subsidies do not always produce positive effects. Excessively high subsidy levels may lead to insufficient investment, thereby preventing the achievement of the intended environmental objectives.Shu sliang et al.[8]examined the impact of technology and sales subsidies on the profits of supply chain members, finding that when government subsidies reach a certain scale, price subsidy models are significantly more beneficial than research and development subsidy models. Dusanee Kesavayuth and Vasileios Zikos[9]found that when the technology spillover effect is high, technological subsidies help improve social welfare, while when the spillover effect is low, output subsidies are more effective in enhancing social welfare.

The innovation of this paper lies in the simultaneous endogenization of blockchain’s influence and blockchain service commission mechanisms, incorporating them into a dual-channel green supply chain decision model. Existing literature often simplifies blockchain technology as an exogenous factor that enhances trust or reduces information asymmetry, neglecting its dual impact on market demand expansion and corporate cost structures. In this study, within the framework of a dual-channel green supply chain, both the market influence effect of blockchain technology (demand expansion) and the service commission constraint of blockchain service fees are simultaneously characterized. This reveals the mechanism of blockchain's dual role in promoting demand and suppressing costs, enriching the modeling approach of blockchain technology within green supply chains.

This paper introduces a research framework that couples blockchain, dual-channel supply chains, and government subsidies, offering a more diversified perspective on dual-channel research. Additionally, this study considers the construction cost of blockchain technology and its influence on the supply chain. By controlling for consistent government subsidy proportions, the analysis compares the profits of supply chain members before and after the application of blockchain technology, as well as under different subsidy policies. This provides targeted recommendations on whether manufacturers should adopt blockchain and participate in government subsidies, aiming to maximize social welfare and enhance the income of supply chain members.

PROBLEM DESCRIPTION AND ASSUMPTIONS

Problem Description

This chapter examines a green manufacturer selling green products through a dual-channel system. The online channel involves the manufacturer adopting blockchain technology for sales, while the offline channel relies on retailers for product distribution. The government can implement three subsidy strategies: no subsidy, technology subsidy, and consumer subsidy, denoted by N, L, and G, respectively.

In practice, green subsidy policies are typically characterized by their ex-ante and institutional nature. Governments determine the subsidy type, subsidy rate, and implementation details in advance within the fiscal budget cycle and publicly announce them. Firms subsequently make their green R&D, pricing, and channel decisions under the established policy framework. Therefore, from both a timing and institutional perspective, firms' decisions are generally responses to a given policy environment. Based on this consideration, the government is modeled as the leader in the Stackelberg game to capture the sequence of "policy setting by the government followed by firms' optimal responses," which allows for a clearer analysis of how different subsidy schemes affect supply chain decisions and social welfare.

The main research questions addressed in this chapter are:

(1)What are the optimal decisions for the manufacturer, retailer, and blockchain service provider under the three government subsidy policies?

(2)Which subsidy policy is most effective in maximizing social welfare?

Symbol Descriptions

The symbols involved in the article are shown in Table 1.

Table 1. Symbolic Variables and Explanations

Symbol	Symbol Description
w	Wholesale price of the product
i	i∈{N,L,G},Government subsidy regime
p_j^i	Selling price in channel j under subsidy regime i
s	Government subsidy rate per unit product
μ	Government subsidy rate for product greenness (technology subsidy)
a	Market demand
γ	Blockchain service commission (commission) ratio
g	Channel cross-price impact coefficient，g>0
θ	Product greenness level
η	Impact coefficient of green technology level on green cost,0<η<1
CS^i	Consumer surplus
SW^i	Social welfare
EI^i	Environmental benefits

Model Assumptions

Assumption 1: Without loss of generality, the manufacturer's basic production cost is normalized to zero.

Assumption 2: Product greenness is used to represent the environmental attribute of the product. A higher level of product greenness implies greater environmental friendliness.

Assumption 3: The effort cost of improving product greenness is given by $C=\frac{1}{2}\eta\theta^2$,where η denotes the impact coefficient of green technology on greenness cost, and θ represents the product greenness level. Government subsidies are assumed to be proportional to the level of product greenness.

Assumption 4: The government's technology subsidy rate for the manufacturer, denoted by μ , satisfies $0<\mu<1$, The unit subsidy provided to consumers, denoted by s , is assumed to be lower than the product price, i.e., $s<p$

Assumption 5: Under the blockchain-enabled sales mode, the adoption of blockchain technology enhances the product's market influence by a factor of $(1+\beta)$. Accordingly, the potential market demand becomes

$(1+\beta)a$, where β represents blockchain influence. A higher value of β indicates a stronger demand-expanding effect of blockchain technology.

Assumption 6: Information between the manufacturer and the government is assumed to be complete and symmetric, see Table 1.

DUAL-CHANNEL GREEN SUPPLY CHAIN MODEL CONSTRUCTION

Dual-Channel Model Without Government Subsidies

When no government subsidy is provided, the green manufacturer sells green products through a dual-channel system. In the online channel, the manufacturer adopts the services of a blockchain technology provider and sells products directly to consumers at the price p_m^B . In the offline channel, the manufacturer wholesales products to a retailer at the wholesale price w^N , and the retailer subsequently sells the products to consumers at the retail price p_r^B .Accordingly, when the government does not implement any subsidy policy, the inverse demand functions for the online and offline channels are given by:

$$p_r^N = a + \lambda\theta - q_r^N - gq_m^N \tag{1}$$

$$p_m^N = (1+\beta)a + \lambda\theta - gq_r^N - q_m^N \tag{2}$$

Here, $a $denotes the potential market size. The parameter g captures the degree of substitutability between the online and offline channels. A larger value of g indicates stronger channel substitutability and more intense channel competition. Due to their environmental friendliness, green products are preferred by consumers; however, they are typically priced higher than conventional products. The green utility derived from the product is represented by $\lambda\theta$, where $$denotes consumers' green preference intensity and $ $represents the product greenness level.The blockchain service provider bears the blockchain construction cost and charges a service fee by extracting a fixed proportion of online sales revenue, denoted by γ as the blockchain commission rate.

The profit functions of the manufacturer and the retailer are respectively given by:

$$\Pi_m^N = (1-\gamma)p_m^N q_m^N + w^N q_r^N - \frac{1}{2}\eta(\theta^N)^2 \tag{3}$$

$$\Pi_r^N = (p_r^N - w^N)q_r^N \tag{4}$$

$$\Pi_p^N = \gamma q_m^N p_m^N \tag{5}$$

By applying backward induction, the optimal decisions of the manufacturer and the retailer under equilibrium can be derived. The following theorem summarizes the optimal outcomes of the manufacturer and the retailer in the traditional dual-channel model.

Theorem 3-1: Under the no-subsidy regime($\eta < \frac{(-2+g)(-6+g+4\gamma)\lambda^2}{2(8+g^2(-3+\gamma))}$), the optimal sales quantities, wholesale price, and product greenness level are given as follows:

$$q_r^N = \frac{2a((2+g(1+\beta)(-2+\gamma))\eta - \beta(-1+\gamma)\lambda^2)}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{6}$$

$$q_m^N = \frac{a(8(1+\beta)\eta - g(2+g+g\beta)\eta + (-2+g)\beta\lambda^2)}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{7}$$

$$w^N = \frac{a((8+g(g(-4+g+g\beta)+2(g-2(1+\beta))\gamma))\eta + 2(-2+g)\beta(-1+\gamma)\lambda^2)}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{8}$$

$$\theta^N = \frac{a(12+g^2(1+\beta)+2g(2+\beta)(-2+\gamma)-8\beta(-1+\gamma)-8\gamma)\lambda}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{9}$$

Theorem 3-1 indicates that when the manufacturer's green R&D cost coefficient η exceeds a certain threshold, a unique optimal equilibrium exists. Substituting the above optimal solutions into Eqs. (1), (4), and (5) yields the optimal profits of the manufacturer, the retailer, and the blockchain service provider.

Technology Subsidy Model

When the government adopts a manufacturer-oriented subsidy policy, it provides a green technology subsidy to encourage the manufacturer to invest in green innovation and adopt environmentally friendly production technologies. Specifically, the government subsidizes the manufacturer's green R&D effort at a rate μ , thereby offsetting a proportion of the green innovation cost $\frac{1}{2}\eta(\theta^L)^2\mu$

The profit functions of the manufacturer, the retailer, and the blockchain service provider are respectively given by:

$$\Pi_m^L = (1-\gamma)p_m^L q_m^L + w^L q_r^L - \frac{1}{2}\eta(\theta^L)^2(1-\mu) \tag{10}$$

$$\Pi_r^N = (p_r^L - w^L)q_r^L \tag{11}$$

$$\Pi_p^N = \gamma q_m^L p_m^L \tag{12}$$

Theorem 3-2: Under the manufacturer technology subsidy regime($\eta > -\frac{(-2+g)(-6+g+4\gamma)\lambda^2}{2(8+g^2(-3+\gamma))(-1+\mu)}$), the manufacturer's optimal wholesale price, product greenness level, and the sales quantities in the blockchain-enabled online channel and the offline retail channel are determined as follows:

$$w^L = \frac{a(-2(-2+g)\beta(-1+\gamma)\lambda^2 + (8+g(g(-4+g+g\beta)+2(g-2(1+\beta))\gamma))\eta(-1+\mu))}{(-2+g)(-6+g+4\gamma)\lambda^2 + 2(8+g^2(-3+\gamma))\eta(-1+\mu)} \tag{13}$$

$$\theta^L = \frac{-((a(12+g^2(1+\beta)+2g(2+\beta)(-2+\gamma)-8\beta(-1+\gamma)-8\gamma)\lambda))}{(-2+g)(-6+g+4\gamma)\lambda^2 + 2(8+g^2(-3+\gamma))\eta(-1+\mu)} \tag{14}$$

$$q_r^L = \frac{2a(\beta(-1+\gamma)\lambda^2 + (2+g(1+\beta)(-2+\gamma))\eta(-1+\mu))}{(-2+g)(-6+g+4\gamma)\lambda^2 + 2(8+g^2(-3+\gamma))\eta(-1+\mu)} \tag{15}$$

$$q_m^L = \frac{a(-((-2+g)\beta\lambda^2) - (-8(1+\beta)+g(2+g+g\beta))\eta(-1+\mu))}{(-2+g)(-6+g+4\gamma)\lambda^2 + 2(8+g^2(-3+\gamma))\eta(-1+\mu)} \tag{16}$$

Theorem 3-2 shows that when the green R&D cost coefficient η exceeds a certain threshold, an optimal equilibrium exists. Substituting the equilibrium solutions into Eqs. (6), (7), and (8) yields the optimal profits of the manufacturer, the retailer, and the blockchain service provider.

$$\Pi_m^L = \frac{a^2(-2\beta^2(-1+\gamma)\lambda^2 + (12+g^2(1+\beta))^2 + 4g(1+\beta)(-2+\gamma) - 8\beta(2+\beta)(-1+\gamma) - 8\gamma)\eta(-1+\mu))}{(2(-2+g)(-6+g+4\gamma)\lambda^2 + 4(8+g^2(-3+\gamma))\eta(-1+\mu))} \tag{17}$$

$$\Pi_r^L = \frac{4a^2(\beta(-1+\gamma)\lambda^2+(2+g(1+\beta)(-2+\gamma))\eta(-1+\mu))^2}{((-2+g)(-6+g+4\gamma)\lambda^2+2(8+g^2(-3+\gamma))\eta(-1+\mu))^2} \tag{18}$$

$$\Pi_p^L = \frac{a^2\gamma((-2+g)\beta\lambda^2+(-8(1+\beta)+g(2+g+g\beta))\eta(-1+\mu))^2}{((-2+g)(-6+g+4\gamma)\lambda^2+2(8+g^2(-3+\gamma))\eta(-1+\mu))^2} \tag{19}$$

Next, we examine the impact of the government's green technology subsidy rate μ on the optimal decisions and profits of the manufacturer, the retailer, and the blockchain service provider.

Corollary 3-1： If $\gamma > \frac{8-g(4-g)}{2(4-g)}$ and $\beta < \beta_1$,or $\gamma < \frac{8-g(4-g)}{2(4-g)}$,Within the feasible region of the model, the wholesale price, product greenness level, online and offline sales quantities, manufacturer profit, and blockchain service provider profit all increase with the subsidy rate μ . $\beta_1 = -\frac{(-2+g)(-6+g+4\gamma)}{(8-8\gamma+g(-4+g+2\gamma))}$

Corollary 3-1 implies that when the government provides a technology subsidy to the manufacturer, the effective cost of green R&D is reduced, inducing the manufacturer to choose a higher product greenness level θ in equilibrium. As $$increases, the manufacturer's marginal production pressure decreases, leading to a significant improvement in product greenness and, consequently, an expansion of market demand. The increase in demand strengthens the manufacturer's market power, resulting in a higher wholesale price w, while both online and offline sales quantities increase accordingly. Due to the joint enhancement of product greenness and market demand, the profits of both the manufacturer and the blockchain service provider rise with the subsidy rate μ .

Price Subsidy Model

When the government adopts a consumer subsidy policy, it provides a unit subsidy s to consumers to encourage the purchase of green products. The subsidy directly reduces the effective purchase price of the green product, such that the price actually paid by consumers becomes $p-s$. Accordingly, the inverse demand functions faced by the blockchain-enabled online channel and the offline retail channel are given by:

$$p_r^G = a+\lambda\theta - q_r^G - gq_m^G + s \tag{20}$$

$$p_m^G = (1+\beta)a+\lambda\theta - gq_r^G - q_m^G + s \tag{21}$$

The corresponding profit functions of the manufacturer, the retailer, and the blockchain service provider are given by:

$$\Pi_m^G = (1-\gamma)p_m^G q_m^G + w^G q_r^G - \frac{1}{2}\eta(\theta^G)^2 \tag{22}$$

$$\Pi_r^G = (p_r^G - w^G)q_r^G \tag{23}$$

$$\Pi_p^G = \gamma q_m^G p_m^G \tag{24}$$

Theorem 3-3: When the government implements the consumer subsidy strategy and the manufacturer's green R&D cost coefficient satisfies($\eta > \frac{(-2+g)(-6+g+4\gamma)\lambda^2}{2(8+g^2(-3+\gamma))}$), the manufacturer's optimal wholesale price, product greenness level, and the sales quantities in the blockchain-enabled online channel and the offline retail channel are determined as follows:

$$w^G = \frac{(-2+g)(a+s)(-4+g(-2+g+2\gamma))\eta + a(2(-2+g)\lambda^2(-1+\gamma) + g(g^2-4\gamma)\eta)\beta}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{25}$$

$$\theta^G = \frac{((-2+g)s(-6+g+4\gamma) + a(12+8\beta+g^2(1+\beta)+2g(2+\beta)(-2+\gamma)-8\gamma-8\beta\gamma))\lambda}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{26}$$

$$q_m^G = \frac{-(((-2+g)(4+g)(a+s) + a(-8+g^2)\beta)\eta) + a(-2+g)\beta\lambda^2}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{27}$$

$$q_r^G = \frac{2(s(2+g(-2+\gamma))\eta + a(2+g(1+\beta)(-2+\gamma))\eta - a\beta(-1+\gamma)\lambda^2)}{2(8+g^2(-3+\gamma))\eta - (-2+g)(-6+g+4\gamma)\lambda^2} \tag{28}$$

Theorem 3-3 indicates that when the manufacturer's green R&D cost coefficient η exceeds the above threshold, a unique optimal equilibrium exists. Substituting the equilibrium solutions into Eqs. (11), (12), and (13) yield the optimal profits of the manufacturer, the retailer, and the blockchain service provider.

$$\Pi_m^G = \frac{\begin{array}{c}(-2+g)s^2(-6+g+4\gamma)\eta + 2as(12+8\beta+g^2(1+\beta)+2g(2+\beta)(-2+\gamma)-8\gamma-8\beta\gamma)\eta + \\ a^2((12+g^2(1+\beta))^2 + 4g(1+\beta)(-2+\gamma) - 8\beta(2+\beta)(-1+\gamma) - 8\gamma)\eta + 2\beta^2(-1+\gamma)\lambda^2)\end{array}}{4(8+g^2(-3+\gamma))\eta - 2(-2+g)(-6+g+4\gamma)\lambda^2} \tag{29}$$

$$\Pi_r^G = \frac{4(s(2+g(-2+\gamma))\eta + a(2+g(1+\beta)(-2+\gamma))\eta - a\beta(-1+\gamma)\lambda^2)^2}{(-2(8+g^2(-3+\gamma))\eta + (-2+g)(-6+g+4\gamma)\lambda^2)^2} \tag{30}$$

$$\Pi_g^G = \frac{\gamma((-2+g)(4+g)(a+s)\eta + a(-8+g^2)\beta\eta - a(-2+g)\beta\lambda^2)^2}{(-2(8+g^2(-3+\gamma))\eta + (-2+g)(-6+g+4\gamma)\lambda^2)^2} \tag{31}$$

Next, we analyze the effects of the government's unit subsidy ss to green consumers on the optimal decisions and profits of the manufacturer, the retailer, and the blockchain service provider.

Corollary 3-2.

When the government provides a unit subsidy for green products, if $\gamma > \frac{8-g(4-g)}{2(4-g)}$ and $\beta < \beta_1$ or if $\gamma < \frac{8-g(4-g)}{2(4-g)}$, the wholesale price, product greenness level, online and offline sales quantities, manufacturer profit, and blockchain service provider profit all increase with the subsidy level s

Corollary 3-2 shows that by lowering the effective purchase price faced by consumers, the consumer subsidy s directly stimulates market demand for green products, leading to significant increases in both online and offline sales quantities. As \$s \$increases, consumers' willingness to purchase green products becomes stronger, and the resulting demand expansion incentivizes the manufacturer to improve product greenness θ . At the same time, the wholesale price w rises due to the demand-driven increase in market power. As total sales expand, both the manufacturer's profit and the blockchain service provider's profit increase with the subsidy level s .

Therefore, the consumer subsidy s essentially functions as a demand-side policy instrument, directly expanding market size by reducing consumers' purchasing costs and indirectly promoting green production and improvements in product greenness.

MODEL ANALYSIS

In this section, we compare the product greenness level, wholesale price, and sales quantities in the online and offline channels under three different government subsidy strategies. To ensure that all optimal solutions are non-negative, the following results are derived under two conditions: $\gamma > \frac{8-g(4-g)}{2(4-g)}$ and $\beta < \beta_3$,or $\gamma < \frac{8-g(4-g)}{2(4-g)}$

Comparison of Product Greenness

Proposition 4-1.By comparing the product greenness levels under the three government subsidy strategies, we get:

(1) $\theta^N < \theta^G$, $\theta^N < \theta^L$

(2)if $s < s_1$, $\theta^L > \theta^G$; if $s > s_1$, $\theta^L < \theta^G$

$$s_1 = \frac{-((2a(8+g^2(-3+\gamma))(12+g^2(1+\beta)+2g(2+\beta)(-2+\gamma)-8\beta(-1+\gamma)-8\gamma)\eta\mu))}{(-2+g)(-6+g+4\gamma)((-2+g)(-6+g+4\gamma)\lambda^2+2(8+g^2(-3+\gamma))\eta(-1+\mu))} \quad (32)$$

Proposition 4-1 shows that different subsidy schemes exhibit significantly different effects on improving product greenness, and their underlying mechanisms also differ.

Technology subsidies directly reduce the manufacturer's green R&D cost. Therefore, under low to moderate subsidy levels, technology subsidies have the most pronounced effect on enhancing product greenness and are more effective in encouraging firms to improve their environmental performance. Although consumer subsidies do not directly affect the manufacturer's R&D cost, they reduce the effective purchase price of green products, thereby stimulating consumer demand and indirectly increasing the manufacturer's incentive to enhance product greenness through demand expansion.

When the subsidy level is small or moderate, technology subsidies generally outperform consumer subsidies in promoting product greenness. However, when consumer subsidies reach a sufficiently high level, their strong demand-stimulating effect induces manufacturers to actively increase product greenness to capture higher profits, in which case consumer subsidies may even outperform technology subsidies.

Therefore, Proposition 4-1 indicates that technology subsidies function as a supply-side cost incentive, whereas consumer subsidies operate as a demand-side market incentive. The resulting change in product greenness depends on the subsidy intensity and the specific incentive channel. Different subsidy strategies dominate in different subsidy ranges.

Comparison of Wholesale Prices

Proposition 4-2.:By comparing the wholesale prices under the three government subsidy strategies, we get:

(1) $w^N < w^G$, $w^N < w^L$

(2)if $s < s_2$, $w^L > w^G$; if $s > s_2$, $w^L < w^G$

$$s_2 = -\frac{\mu a(12+g^2(1+\beta)+2g(2+\beta)(-2+\gamma)-8\beta(-1+\gamma)-8\gamma)\lambda^2}{(-2+g)(-6+g+4\gamma)\lambda^2+2(8+g^2(-3+\gamma))\eta(-1+\mu)} \quad (33)$$

Proposition 4-2 shows that government subsidies not only affect production costs or consumer prices but also alter the manufacturer's incentives in wholesale pricing. In general, technology subsidies reduce R&D costs and enhance product greenness, thereby strengthening the manufacturer's pricing power, which leads to higher wholesale prices compared with the consumer subsidy and no-subsidy cases. Although consumer subsidies do not directly reduce production costs, they expand market demand, prompting manufacturers to raise wholesale prices in order to extract higher profits.

When the subsidy level is relatively low, the positive effect of technology subsidies on wholesale prices is typically stronger than that of consumer subsidies. However, as consumer subsidies increase beyond a certain threshold, the strong demand expansion effect begins to dominate, resulting in higher wholesale prices under consumer subsidies and stronger pricing incentives for manufacturers.

This implies that wholesale price adjustments depend jointly on green R&D costs and market demand size. Technology subsidies primarily alleviate cost-side pressures, whereas consumer subsidies exert influence through demand expansion. Consequently, their impacts on wholesale pricing exhibit clear threshold and interval characteristics.

Comparison of Sales Quantities

Proposition 4-3.

By comparing the sales quantities in the blockchain-enabled online channel and the offline retail channel under the three government subsidy strategies, we get：

(1) $q_m^N < q_m^G$, $q_r^N < q_r^G$; $q_m^N < q_m^L$, $q_r^N < q_r^G$

(2)if $s < s_1$, $q_m^L > q_m^G$, $q_r^L > q_r^G$; if $s > s_1$, $q_m^L < q_m^G$, $q_r^L < q_r^G$.

Proposition 4-3 indicates that the optimal sales quantities in both online and offline channels display markedly different patterns across the three subsidy schemes. Consumer subsidies directly reduce consumers' purchase costs and therefore most effectively stimulate market demand, resulting in substantial increases in sales in both channels. Although technology subsidies do not affect consumer prices, they enhance product greenness and thus indirectly expand demand, leading to higher sales than in the no-subsidy case, albeit with a weaker effect than consumer subsidies.

When subsidy levels are small or moderate, consumer subsidies generally yield the most significant increase in sales for both the blockchain-enabled channel and the offline retail channel. As consumer subsidies enter a high-subsidy range, their demand-expansion effect becomes even more pronounced, causing sales volumes under consumer subsidies to significantly exceed those under other subsidy schemes.

Therefore, Proposition 4-3 suggests that technology subsidies mainly increase sales by improving product attributes, whereas consumer subsidies directly stimulate demand by lowering purchase prices and thus exhibit stronger marginal effects on sales growth. The impact of different subsidy strategies on sales structures depends on both the direction and intensity of the subsidies.

In practice, government subsidy budgets are limited and constrained by various factors. To facilitate a fair comparison of policy effectiveness, we assume that the total subsidy expenditure is identical under the manufacturer subsidy and consumer subsidy schemes, denoted by S .Accordingly, the total government subsidy expenditures under the two policies are given by:

$$S = \frac{1}{2}\eta(\theta^G)^2\mu \tag{34}$$

$$S = s(q_r^G + q_m^G) \tag{35}$$

Based on these expressions, the equilibrium outcomes under the three subsidy strategies can be reformulated in terms of the total subsidy budget S. However, the resulting analytical expressions are highly complex and not conducive to tractable theoretical analysis. Therefore, in the next section, we employ numerical experiments to examine the impacts of different subsidy policies on the manufacturer, retailer, blockchain service provider, consumers, and overall social welfare under a fixed government subsidy budget. The objective is to identify the conditions under which each subsidy strategy maximizes social welfare.

NUMERICAL EXPERIMENTS

In this section, a set of parameter values is specified as follows:

$$a = 4, g = 0.3, \eta = 1, \gamma = 0.2, \lambda = 0.2, \beta = 0.4 \tag{36}$$

Numerical experiments are conducted to investigate how the government's total subsidy expenditure affects the optimal decisions and performance of the manufacturer, retailer, and blockchain service provider, as well as consumer surplus in the online and offline channels, environmental benefits, and overall social welfare.

To ensure that government expenditures are identical under the manufacturer subsidy and consumer subsidy schemes, the technology subsidy rate $$is adjusted correspondingly as the unit consumer subsidy s varies. When $\mu = [00.20.40.60.8]$, the corresponding values of the unit consumer subsidy in the consumer subsidy model are calculated as [0 $0.0176 \ \ 0.0634 \ \ 0.2172 \ \ 1.1414$]

Based on these settings, we analyze the effects of changes in government subsidy expenditure on the performance of green product supply chain members. The numerical results are illustrated in Figures 1 to 4.

Effects of Government Subsidies on Optimal Decisions

Impact on Product Greenness

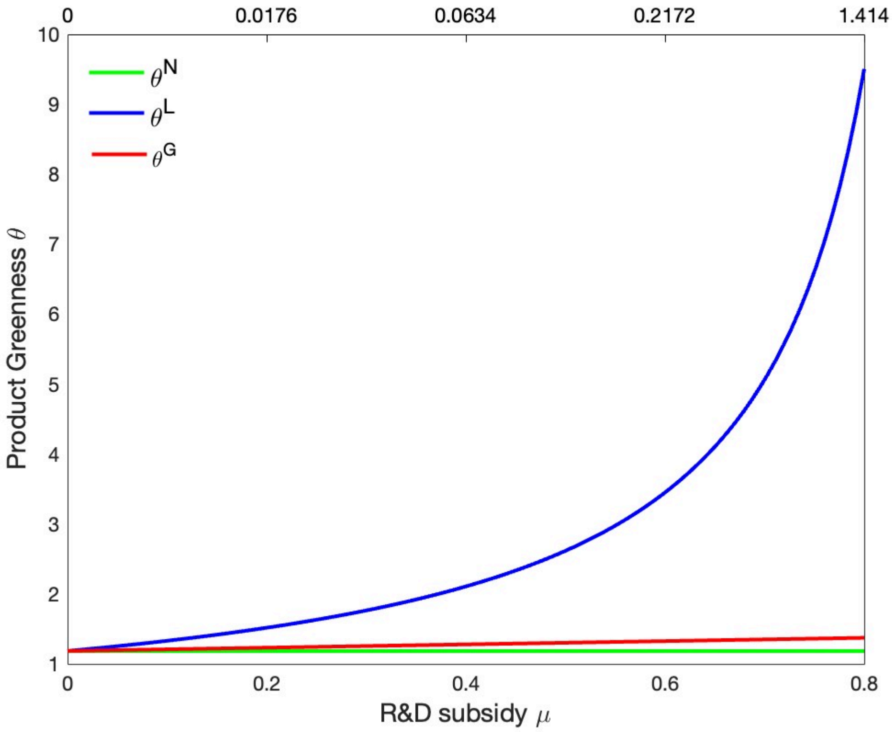

Figure 1. Impact of Government Subsidies on Product Greenness

Compared with the no-subsidy scenario, the presence of government subsidies always leads to an increase in the wholesale price. According to the analytical results derived earlier, government subsidies incentivize manufacturers to improve product greenness, which in turn motivates them to raise the wholesale price of green products.

Moreover, when the total government subsidy expenditure is held constant, neither subsidizing manufacturers nor subsidizing consumers consistently results in a higher wholesale price. Instead, the outcome depends on the size of the subsidy budget. When the total subsidy level is relatively low, subsidizing manufacturers leads to a slightly higher wholesale price than subsidizing consumers. In contrast, when the total subsidy exceeds a certain threshold, consumer subsidies result in a higher wholesale price than manufacturer subsidies, and this gap becomes increasingly pronounced as the government subsidy budget expands.

Impact on Wholesale Prices

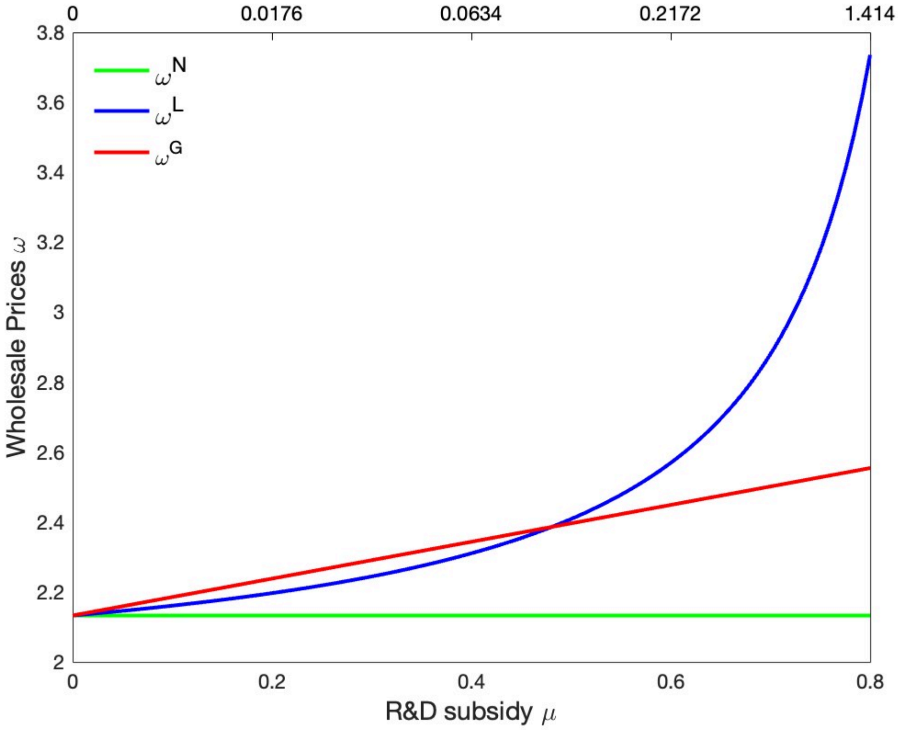

Figure 2. Impact of Government Subsidies on Wholesale Prices

As the subsidy level increases, the wholesale price set by the manufacturer exhibits an overall downward trend. This occurs because government subsidies effectively reduce the manufacturer's costs associated with green production and technological investment, thereby providing greater flexibility in pricing decisions while maintaining profitability. To expand market demand and increase channel sales, manufacturers are inclined to lower wholesale prices in order to stimulate retailers' order quantities.

Furthermore, as the subsidy level rises, the manufacturer's incentive to adopt a "price-for-volume" strategy becomes stronger, allowing scale benefits to be realized through increased sales volumes, which further suppresses the wholesale price. These findings indicate that government subsidies not only directly influence green investment decisions but also reshape channel structures through price mechanisms.

Impact on Supply Chain Members' Profits

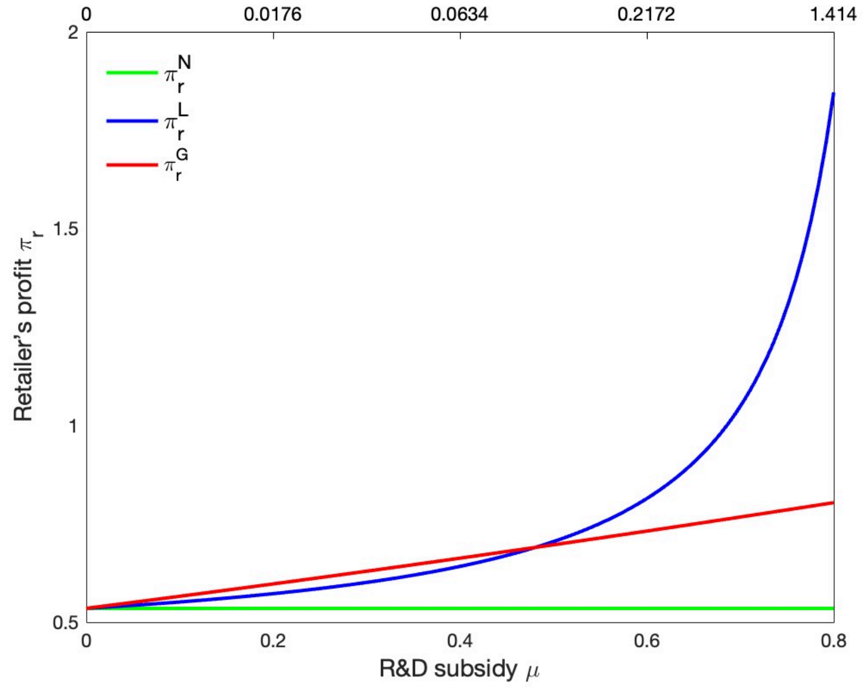

Figure 3. Supply Chain Members' Profits

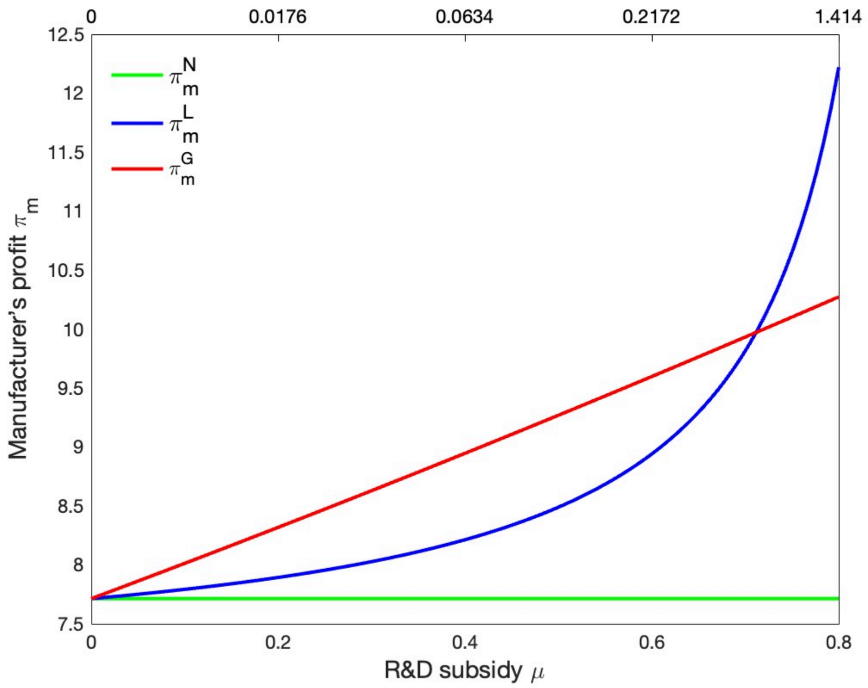

Figure 3. Supply Chain Members' Profits

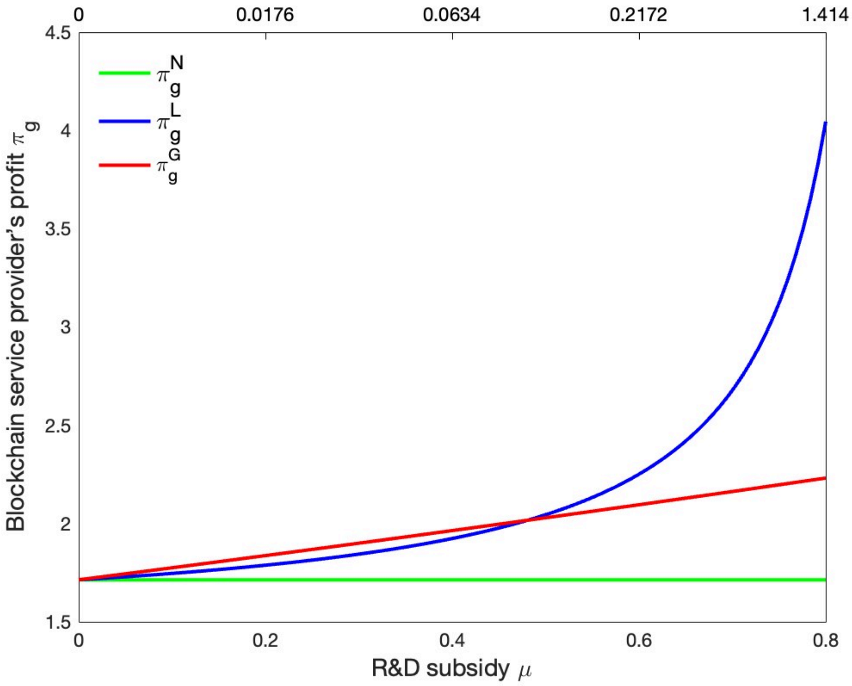

Figure 3. Supply Chain Members' Profits

Government subsidies exert significant impacts on the decisions and profitability of supply chain members by reducing green investment costs and amplifying demand effects. For manufacturers, subsidies directly alleviate the cost constraints associated with green technological investment, encouraging higher product greenness and more competitive pricing strategies, which in turn stimulate sales growth and improve profit levels.

For retailers, subsidies transmitted through upstream green decisions and wholesale pricing promote downstream market expansion. Although intensified channel competition may arise, retailers' overall profits still improve to varying degrees. For blockchain service providers, subsidies expand online sales volumes, thereby increasing the fee base from which service revenues are derived, making them direct beneficiaries of subsidy policies.

Overall, government subsidies play a clear coordinating role in green dual-channel supply chains. On the one hand, subsidies improve incentive compatibility and profitability among manufacturers, retailers, and blockchain service providers. On the other hand, by increasing consumer surplus and environmental benefits, subsidies enhance overall social welfare. The simulation results demonstrate that, under an appropriate subsidy intensity, government subsidies can simultaneously achieve economic benefits, environmental improvements, and supply chain performance optimization.

Impact on Consumer Surplus

When the government does not provide subsidies, the consumer surplus in the online channel and the offline retail channel can be derived:

$$CS_m^N = \frac{1}{2}(q_m^N)^2 \tag{37}$$

$$CS_r^N = \frac{1}{2}(q_r^N)^2 \tag{38}$$

accordingly. Similarly, under the manufacturer subsidy and consumer subsidy schemes, the consumer surplus in both channels can be obtained.

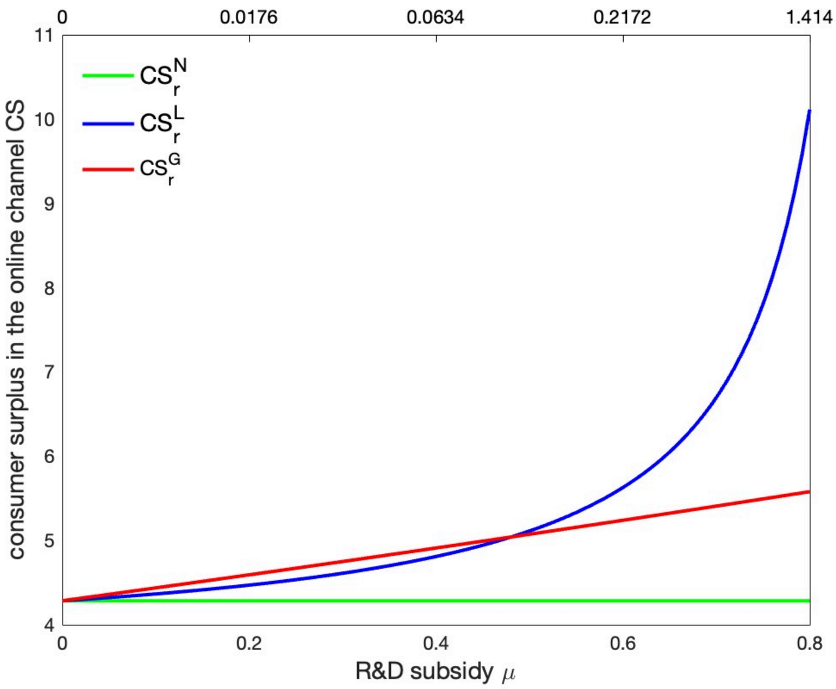

Figure 4. Effects of Government Subsidies on Consumer Surplus

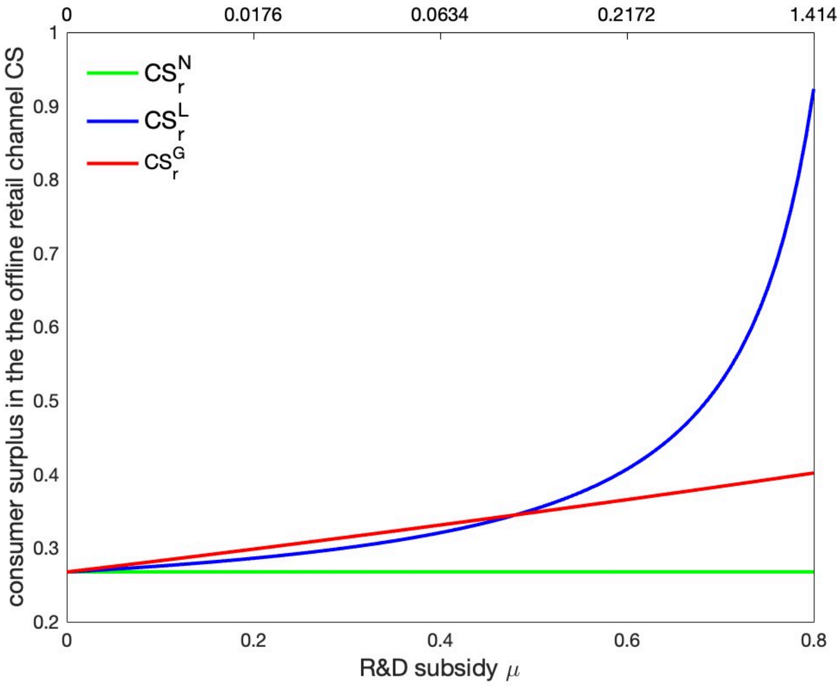

Figure 4. Effects of Government Subsidies on Consumer Surplus

As illustrated in Figure 4, compared with the no-subsidy scenario, consumer surplus increases monotonically with the level of government subsidies. On the one hand, subsidies encourage manufacturers to lower wholesale prices and final retail prices, thereby reducing consumers' payment burdens. On the other hand, improvements in product greenness enhance consumers' utility derived from the environmental attributes of green products. The combined effects of price reductions and utility enhancement allow consumers to purchase higher-quality and greener products at lower effective prices, leading to a substantial increase in consumer surplus. These results indicate that government subsidies not only improve production-side decisions but also significantly enhance consumer welfare, see Figure 5.

Impact on Environmental Benefits

Environmental benefits are defined as $EI^i = \theta^i(q_m^i + q_r^i)$

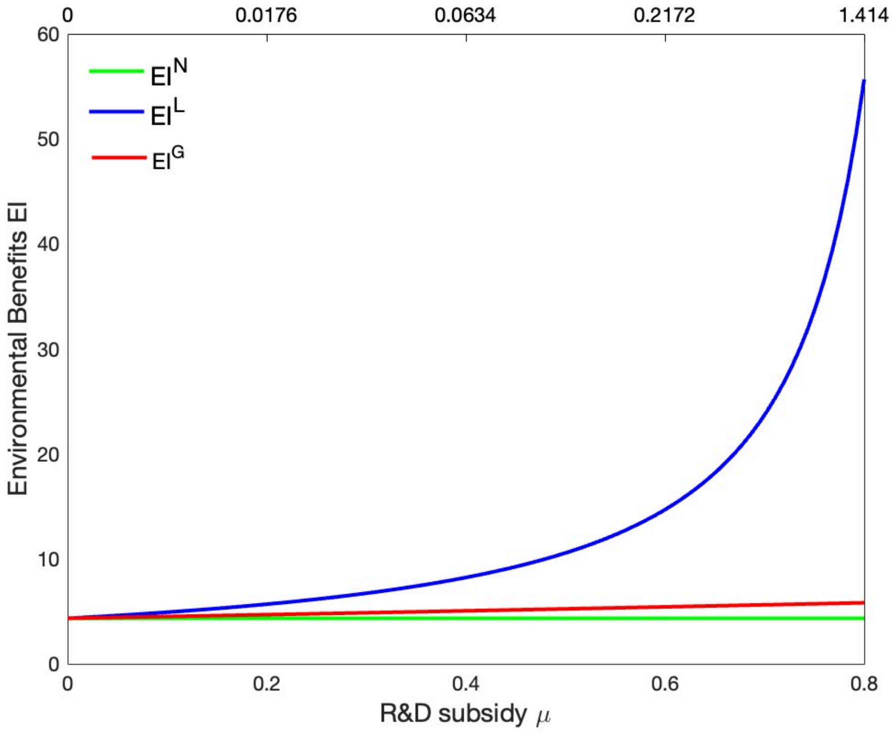

Figure 5. Effects of Government Subsidies on Environmental Benefits

Simulation results show that government subsidies have a significant positive effect on environmental performance. As the subsidy level increases, manufacturers continue to enhance product greenness, improving the environmental friendliness of each product and thereby reducing the negative environmental impacts during production and consumption, see Figure 5.

Although the increase in sales volume may bring some scale effects, the improvement in greenness is more pronounced, and overall environmental benefits continue to rise. This shows that government subsidies can incentivize green technology investments, achieving a balance between economic growth and environmental protection, see Figure 6.

Impact on Social Welfare

Social Welfare is defined as $SW^i = EI^i + CS_j^i + \pi_j^i - S$

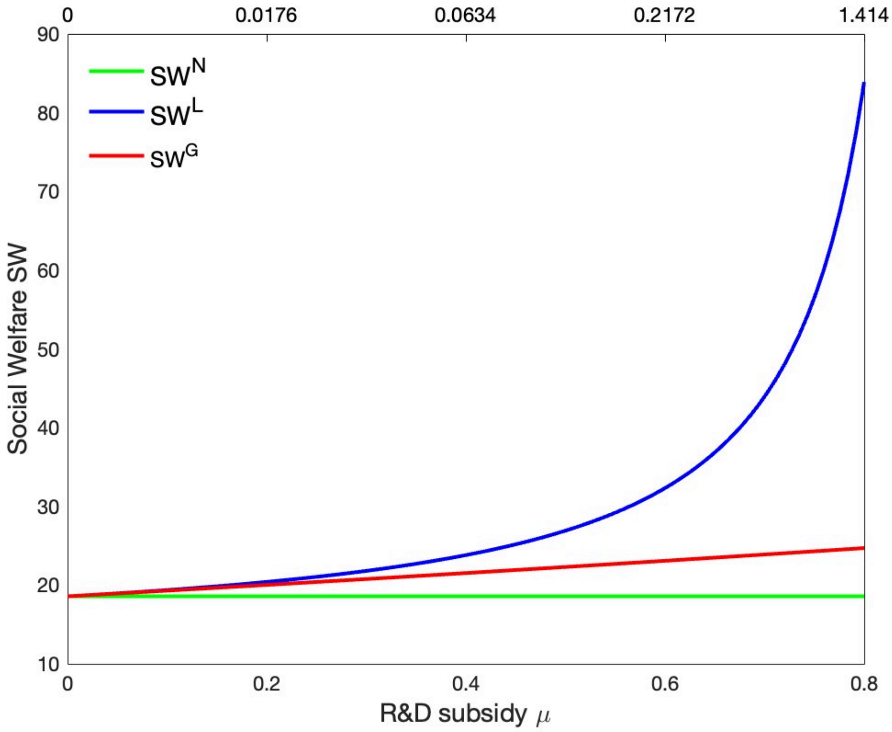

Figure 6. Impact of Government Subsidies on Social Welfare

From the perspective of social welfare, simulation results show that increasing government subsidy levels significantly enhances overall social welfare. Profits for manufacturers, retailers, and blockchain suppliers improve under the subsidy policy, while consumer surplus and environmental benefits also increase, leading to a rise in overall social welfare, see Figure 6.

Although government subsidies entail fiscal expenditure, the combined benefits from promoting green production, expanding market demand, and improving environmental performance can offset or even exceed the cost of the subsidies. Therefore, moderate government subsidies have a clear effect on improving social welfare in the green product dual-channel supply chain.

Impact of Government Green Innovation Technology Subsidy Rate on Retailer Profits

Next, we analyze the impact of government green innovation technology subsidy rates μ on retailer profits by considering different blockchain influence levels $\beta = 0.2$、0.5、0.8 .Using numerical experiments, we explore how changes in the green innovation technology subsidy rate affect retailer profits, see Figure 7.

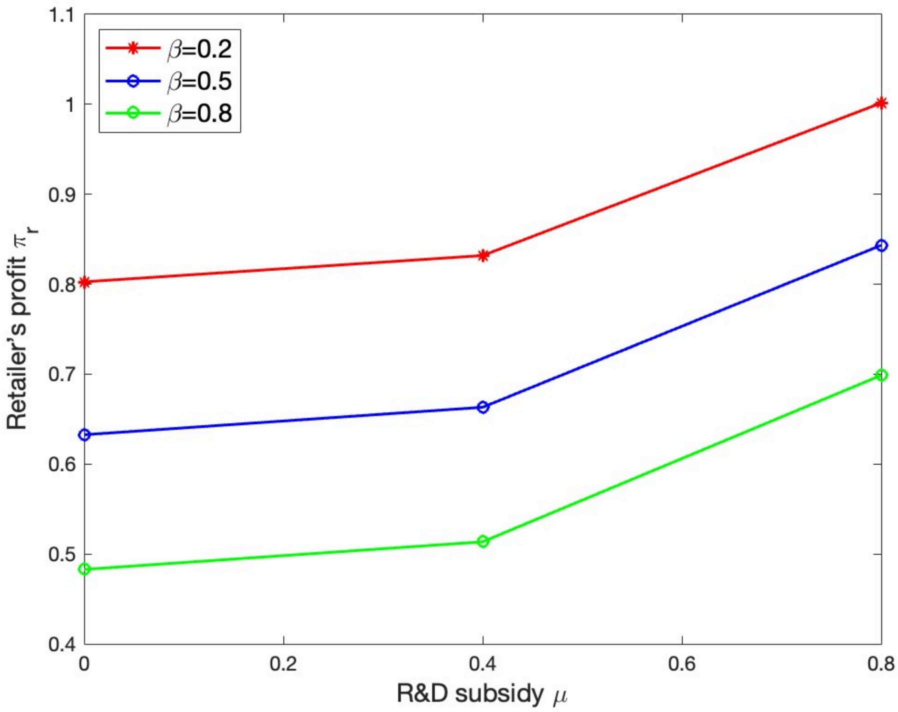

Figure 7. Impact of Government R&D Subsidy Rate on Retailer Profits

From Figure 7, it can be observed that, regardless of the blockchain influence, the higher the government green innovation technology subsidy rate μ , the higher the retailer 's profit. This indicates that the increase in revenue brought by higher green product sales exceeds the increase in procurement costs, leading to "free rider" behavior among retailers. Furthermore, the increase in blockchain influence reduces retailer profits. This is because stronger blockchain influence gives manufacturers greater channel power, reducing their dependence on offline retail channels. To maximize profits, manufacturers will choose to increase wholesale prices.

CONCLUSION

Based on the blockchain dual-channel green supply chain model, this paper introduces government subsidy policies and constructs a decision model for green products in a dual-channel supply chain with government participation. The research findings provide practical guidance for the green and digital transformation of the textile industry. It systematically analyzes the impact of government subsidies on supply chain member decisions, market performance, and social welfare. By combining theoretical derivation and numerical simulations, this paper focuses on examining the mechanisms through which changes in subsidy levels affect product greenness, pricing strategies, sales volume, and the profits of supply chain members.

The following conclusions and insights are drawn from the study of green manufacturers and blockchain dual-channel government subsidies:

(1) Government subsidies can effectively improve the greenness and market sales of green products, thereby increasing the profits of manufacturers, retailers, and blockchain suppliers, and promoting social welfare. Government subsidies not only support manufacturers' research and innovation but also help promote and popularize green products. Therefore, the government should actively formulate subsidy policies to support the development of green technologies and the promotion of green products.

(2) When the total government subsidy is the same, green technology subsidies are more effective in enhancing product greenness, environmental benefits, and social welfare, while price subsidies are more effective in increasing product sales, improving profits for supply chain members, and boosting consumer surplus. Therefore, the government should choose the appropriate subsidy policy based on the subsidy budget and specific objectives. If the goal is to enhance environmental benefits and social welfare, the government should prioritize technology subsidies. If the goal is to promote the popularization of green products, consumer subsidies will be more effective.

FUTURE RESEARCH

(1) introduce a more detailed cost structure by distinguishing between conventional and green material costs, establishing a heterogeneous production cost model. This would better capture the relationship between cost and greenness in green supply chains and analyze the impact of cost structure on optimal green investment, pricing strategies, and the effectiveness of government subsidies.

(2) Regarding blockchain service models, future studies could consider cost-sharing mechanisms among multiple stakeholders and the differentiated application of blockchain across channels, examining its effects on channel substitution and overall supply chain decisions.

Author Contributions

1. Jianhua Wang contributed to the literature review, numerical analysis, discussion of results.

2. Wenxin Zhang contributed to model development, data analysis, manuscript writing.

Conflicts of Interest

The authors declare no conflict of interest.

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Data Sharing Agreement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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