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Research Article

Research on the Coordination of Fresh Food Supply Chain Based on the Perspective of Blockchain and Low Carbon

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We consider a three-stage fresh agricultural product supply chain consisting of a supplier, a third-party logistics service provider (TPLSP), and a retailer and discuss the coordination mechanism of "revenue sharing + double cost sharing" contracts and "two-part tariff + revenue sharing + double cost sharing" contracts between the supplier, TPLSP, and the retailer. Based on this, we not only explore the conditions for supply chain full coordination and Pareto improvement but also analyze the effect of blockchain technology application cost, consumer environmental protection awareness, freshness preference, green trust level on carbon emission reduction level, fresh-keeping effort level, price decisions, and profits by comparing three different decision-making models. Results show that the improvement of the green trust level can help to improve the carbon emission reduction level, fresh-keeping effort level, price decisions, and profits. The application of blockchain technology can reduce transaction costs and improve consumer green trust levels, thereby increasing market demand and profits. When environmental protection awareness and freshness preference are higher than a certain value, the unit retail price of fresh products under decentralized decision-making is the highest with the blockchain technology applied. TPLSP can increase the wholesale, service, and retail prices of fresh products by appropriately increasing the blockchain technology application cost-sharing ratio. When $15 < T_1 < 29.2416$ and $47 < T_2 < 66.0408$, "two-part tariff + revenue sharing + double cost sharing" contracts can achieve the Pareto improvement.

1. Introduction

In January 2020, the Ministry of Agriculture of China issued the "Digital Agriculture and Rural Development Plan" which pointed out that the innovative application of blockchain technology in quality, safety traceability, and supply chain information transparency should be developed. In September 2020, the Chinese government put forward at the United Nations General Assembly: "China strives to achieve carbon peaking by 2030 and carbon neutrality by 2060." Based on these policies, in November 2021, the State Council of China promulgated ""The 14th Five-Year" Cold Chain Logistics Development Plan" pointed out that the development of cold chain logistics can expand the supply in high-quality markets and meet different consumption needs of the people. It is an important guarantee for improving the quality and safety system of fresh agricultural products and building a healthy China. It is also proposed to speed up the application of blockchain technology in the construction of cold chain logistics intelligent monitoring and traceability system to improve the authenticity, timeliness, and credibility of traceability information. At the same time, since cold chain logistics warehousing, transportation, and other links require quite a lot of energy consumption, achieving carbon peak and carbon neutrality puts forward some new requirements for the low-carbon development of cold chain logistics, thus encouraging the application of green, safe, energy-saving, and environmentally friendly refrigerated trucks as well as the use of high-efficiency, low-carbon refrigeration agents, and insulation materials.

Fresh agricultural products are indispensable commodities in people's daily life. They have the characteristics of seasonal supply and are easy to deteriorate, which may cause great losses in the process of logistics [1, 2]. According to the statistics, the annual loss rate of fresh agricultural products in China ranges from 25% to 35% [3]. Therefore, fresh agricultural products need precise control over the temperature and humidity during transportation and storage. Under this demand, many third-party logistics providers (TPLSPs) with cold chain technology have emerged, and the three-tier supply chain composed of suppliers, TPLSPs, and retailers have become one of the main logistics modes for fresh products. With the intensification of international competition and the popularization of the concept of low-carbon environmental protection, the "carbon label" has become an important factor affecting the export of fresh products in China [4]. Therefore, TPLSPs should reduce carbon emissions as much as they could in the process of low-temperature storage and cold chain transportation of fresh agricultural products.

In addition, in recent years, consumers' awareness of environmental protection has gradually increased, resulting in their will to pay higher prices for high-quality fresh products. The carbon emission reduction level in the logistics process and the freshness of fresh products have become the decisive indicators for consumers' choices. As supply chain companies may have problems such as information fraud and false reporting, consumers cannot have absolute green trust in them, thus affecting the demand for fresh products. As an immutable, open, and transparent database, blockchain technology plays a positive role in the green operation of the fresh agricultural product supply chain [5]. The application of blockchain technology by enterprises enables consumers to understand products' real information and effectively solve the green trust problem of consumers when purchasing fresh products [6, 7], when the "smart contract technology" in the blockchain enables enterprises to strengthen the level of collaborative operation, improve operational efficiency, and reduce transaction costs [8, 9]. Therefore, it is of great significance to study the coordination of fresh agricultural product supply chains from the perspective of blockchain and low-carbon.

We tend to study the following questions:

(1) In the tertiary fresh agricultural product supply chain, what is the impact of consumers' green trust level, environmental protection awareness, freshness preference, and application cost of blockchain technology on the decision-making and profits of the supply chain system?

(2) Does the application of blockchain technology have a positive impact on the supply chain system? Are the decisions and profits of each enterprise in the supply chain under the centralized decision-making model better than the optimal results under the decentralized decision-making model?

(3) How to design an effective contract incentive mechanism to improve the operation efficiency of the supply chain in order to increase the participants' profits in the supply chain?

In order to answer the questions mentioned above, this paper constructs a three-stage fresh agricultural product supply chain dominated by a TPLSP, followed by a supplier and a retailer, with contractual coordination among the three parties. We first compare the decision-making and profits of the fresh agricultural product supply chain system without the application of blockchain technology under decentralized decision-making and when blockchain technology is applied. For the situation where the benefits are higher, we analyze the supply chain participants' decisions and profits in the centralized decision-making mode. Then, we introduce the contract incentive mechanism to explore the conditions of sufficient coordination and Pareto improvement areas to maximize the profits of the supply chain system or achieve a triple-win situation. Finally, we verify the impact of various factors and coordination contracts on the decision-making and profits of the supply chain system through numerical example simulation analysis.

In conclusion, the present study contributes to the literature from the following two aspects:

(1) This paper comprehensively considers that the fresh agricultural products demand is affected by the retail price, carbon emission reduction level, fresh-keeping effort level, consumer freshness preference, environmental protection awareness, and green trust level, studies the decision-making issues of supply chain pricing, fresh-keeping, and carbon emission reduction, and expands the research scope of factors affecting the supply chain of fresh agricultural products and the theory of low-carbon supply chain operation and management

(2) This paper compares and analyzes the decision-making results of the fresh agricultural product supply chain before and when blockchain technology is applied and designs two combined contracts for coordination, which enriches the research direction of the fresh agricultural product supply chain decision-making, refines and enriches the supply chain coordination mechanism, and provides help for solving related practical problems

We organize the rest of this paper as follows. Section 2 reviews the relevant literature at home and abroad and puts forward the innovations of this paper. Section 3 shows the problem statement, constructs a three-level agricultural product supply chain model, compares and analyzes the optimal decision-making and profits of the supply chain system under different decision-making modes, and analyzes the feasibility and coordination conditions of the two contract incentive mechanisms. Section 4 verifies the previous analysis results through mathematical analysis and various numerical examples. Section 5 presents managerial insights and practical implications. Section 6 summarizes our findings and outlook. All the proof procedures in this paper are given in the appendix.

2. Literature Review

At present, related research can be summarized into three aspects: (1) research on the coordination of fresh agricultural product supply chain, (2) carbon emission reduction in the supply chain, and (3) applications of blockchain technology in the supply chain.

2.1. Research on the Coordination of Fresh Agricultural Product Supply Chain.

So far, many researchers have studied the coordination of the fresh agricultural product supply chain. For example, Alinezhad et al. [10] analyzed a case study problem in the perishable product industry, and the results demonstrated the superiority of the Lp metric over goal-achieving methods. Tirkolaee and Aydin [11] optimized a sustainable multilevel multiproduct supply chain and combined transportation network for perishable product distribution by introducing a fuzzy two-level decision support system. The above-given literature proposes new methods to optimize the supply chain of fresh agricultural products. At the same time, coordination contracts have also become an effective way to improve the efficiency of supply chain profits and operational collaboration. Cachon [12] summarized several commonly used supply chain contract coordination mechanisms and concluded that for the fresh product cold supply chain, revenue-sharing contracts, cost-sharing contracts, and repurchase contracts are the most common coordination contracts. Hu and Feng [13] constructed a supply chain model with service demand under the situation of uncertain supply and demand, designed a revenue-sharing contract, and analyzed the optimal decision-making of buyers and suppliers along with the feasible conditions for coordinating supply chains.

The above-given literature only designs a single contract incentive mechanism to coordinate the supply chain, but subsequent research shows that the combined contract is more advantageous and applicable. For instance, Yan et al. [14] constructed a fresh agricultural product supply chain considering strategic consumer behavior and solved the problems in decentralized decision-making by designing two contract incentive mechanisms based on revenue sharing and wholesale price. The study of Pang et al. [15] found that revenue-sharing contract alone could not achieve perfect coordination of the three-stage supply chain consisting of one manufacturer, one distributor, and one retailer, but when combined with the constraints of rebate and penalty contracts, it can coordinate the supply chain well. Due to the advancement of cold chain technology, there have been many third-party logistics service providers (TPLSPs) that provide fresh food preservation and distribution services. Therefore, on the basis of the above-given literature, it is necessary to conduct a coordinated study on the fresh food supply chain in which TPLSP participates. Ma et al. [16] studied the decision-making and system profits of each member in the three-stage supply chain system which consists of farmers, third-party logistics providers (TPLPs), and retailers and designed a combination of “cost sharing + revenue sharing.” This coordination mechanism makes every participant’s profits in the supply chain achieve Pareto improvement. Although the above-given literature studies the coordination of the supply chain of fresh agricultural products, the research perspective and the setting of influencing factors are relatively simple. On this basis, this paper considers the supply chain coordination research from the perspective of low carbon and blockchain and analyzes the impact of consumer environmental protection awareness, freshness preference, and green trust level on decision-making and profits in the fresh agricultural product supply chain.

2.2. Carbon Emission Reduction in the Supply Chain.

Nowadays, as people’s low-carbon and environmental protection awareness increases, their preference for green products increases as well; when global warming puts forward new requirements for carbon emissions, the issue of carbon emission reduction in the supply chain has also become a research hotspot in academia [17, 18]. For example, Hu et al. [19] studied how companies make optimal carbon emission reduction decisions in a low-carbon environment. Dai and Wang [20] and Chai et al. [21] studied the influences of carbon emission constraints on supply chains in different market scenarios. Based on this, Das et al. [22] further studied the impact of carbon tax policy in the multiobjective green physical logistics model under sustainable development. The above-given literature considers carbon emission reduction in the supply chain [23, 24] but does not consider the particularity of the fresh agricultural product supply chain. Bai et al. [25] constructed a fresh food supply chain dominated by suppliers, followed by manufacturers and two retailers, in which they analyzed the impact of carbon policies on optimal decisions and profits. Mishra et al. [26] believed that price and inventory levels were the main factors affecting the demand for fresh products, they, therefore, constructed and analyzed an optimal inventory control model for fresh products.

It can be seen from the previous literature that most products generate carbon emissions during production and processing [27, 28], and the carbon emissions of fresh agricultural products are mainly generated by low-temperature storage and cold chain transportation to maintain freshness. Therefore, on this basis, this paper constructs a three-stage fresh agricultural product supply chain with TPLSP as the leading enterprise and then analyzes the main factors that affect TPLSP fresh-keeping, carbon emission reduction, and pricing decisions.

2.3. Applications of Blockchain Technology in the Supply Chain.

In recent years, the application of blockchain technology in supply chain research has attracted the attention of many researchers [29]. Saberi et al. [30] found that blockchain technology can break the information barriers between supply chain enterprises and play a positive role in promoting the innovation of supply chain finance. Li et al. [31] designed a “blockchain + collaborative emission reduction” information sharing mechanism to improve the supply chain revenue, thus solving the problem of reduced efficiency of supply chain coordinated emission reduction caused by consumers’ nondisclosure of low-carbon preferences. The above-given literature further considers the impact of the application of blockchain technology on the supply chain but does not consider the impact of blockchain technology on carbon emission reduction and the fresh agricultural product supply chain. In terms of carbon reduction, Manupati et al. [32] designed a distributed ledger-based blockchain approach to address various production distribution issues in multilevel supply chains under carbon tax policies. Zhang et al. [33] constructed a three-stage supply chain composed of the government, manufacturers, and retailers, then analyzed the supply chain's optimal carbon emission reduction rate, low-carbon product output, and social welfare application under four scenarios with or without the application of blockchain technology and two kinds of government subsidies. They also studied the optimal strategy of government low-carbon subsidies. In terms of the fresh agricultural product supply chain, Xu et al. [34] found that the application of blockchain technology by manufacturers can not only improve the greenness of products but also help optimize and coordinate supply chains. He et al. [35] studied the impact of blockchain technology on the pricing decisions and profits of participants in the global fresh agricultural product supply chain. Cui and Yao [36] constructed an evolutionary game model of an agricultural product supply chain using blockchain technology and discussed the key factors that affect participants' compliance with the rules of blockchain nodes. The above-given literature has studied the role of blockchain technology in the low-carbon supply chain and the supply chain of fresh agricultural products, respectively, but there is no literature that considers the impact of applying blockchain technology on the supply chain of low-carbon fresh agricultural products. Therefore, this paper will study this issue.

2.4. Research Gap. To sum up, most existing literature only consider the impact of a single or partial factors such as the retail price of fresh products, carbon emission reduction, or freshness on market demand and ignores the level of consumer green trust's effects on demand, prices, levels of carbon reduction, and fresh-keeping efforts [37, 38]. There are many studies on the application of blockchain technology in low-carbon supply chains or agricultural product supply chains, but few scholars have studied the three-stage fresh agricultural product supply chain from the perspective of blockchain and low-carbon, and there is also room for improvement in coordination contracts. Therefore, this paper considers the three-stage supply chain system dominated by TPLSP, followed by suppliers and retailers and studies the decision-making and coordination problems of this system under the application of blockchain technology.

As shown in Table 1, a comparison with previous literature shows that the innovations and advantages of this paper are as follows: first, this paper considers the comprehensive impact of the retail price, environmental protection awareness, freshness preference, and green trust level on the demand for fresh agricultural products. Second, this paper explores the impacts of the application of blockchain technology, carbon emission reduction and fresh-keeping cost coefficients, consumer behavior preferences and other factors on the level of preservation efforts, carbon emission reduction levels, pricing decisions, and the profits of each main body in the supply chain. Third, this paper compares the decision-making and profits of the three-stage fresh food supply chain system under decentralized decision-making with and without the application of blockchain technology, on which we base to provide theoretical support for the decision-making of suppliers, retailers, and TPLSP. Fourth, this paper compares the decision-making and benefits of the supply chain system under the decentralized and centralized decision-making mode when applying blockchain technology, before designing the contracts of "revenue sharing + double cost sharing," and "two-part tariff + revenue sharing + double cost sharing" incentive mechanism to achieve the perfect coordination of profits among the main bodies of the supply chain system.

Therefore, in a theoretical sense, based on low-carbon theory and blockchain technology theory, this paper expands the research scope of fresh agricultural product supply chain decision-making and refines and enriches the supply chain coordination mechanism by designing two combined contracts. In a practical sense, this paper can achieve the purpose of encouraging TPLSP to improve the level of fresh-keeping efforts and carbon emission reduction, consumers to improve freshness preference and environmental protection awareness and to expand market demand for high-quality fresh agricultural products. Then, this paper can promote the green and sustainable development of the fresh agricultural product supply chain and make a certain contribution to strengthening the ecological environmental protection and improving the overall social benefits.

3. Problem Statement

3.1. Problem Statement. As shown in Figure 1, this paper considers a three-stage fresh agricultural product supply chain consisting of a supplier, a retailer, and a third-party logistics service provider (TPLSP), where supply chain enterprises apply blockchain technology for a fee, and transaction cost is reduced by applying blockchain technology. TPLSP is the leading enterprise which provides services such as low-temperature storage and cold chain transportation to achieve the effect of keeping fresh products fresh. During this process, the electricity consumed by air-conditioned storage and cold storage is the main source of carbon emissions. Consumers have environmental protection.

Awareness and freshness preference, also doubt the emission reduction and freshness information provided by enterprises, thus affecting the market demand. TPLSP makes decisions about fresh product service price, carbon emission reduction level, and fresh-keeping effort; it publishes information such as carbon emission reduction level and freshness through the blockchain technology application platform, allowing consumers to use blockchain technology to trace the source of products, which, in turn improves Green trust level. Suppliers determine the wholesale price based on TPLSP and their own production costs, while retailers estimate market demand and determine the retail price based on TPLSP and suppliers' decisions.

Table 1: Survey of fresh agricultural product supply chain.

Reference	Supply chain system	Demand-influencing factors							Coordination contract	Consider low-carbon	Technology application
		Retail price	Fresh-keeping effort level	Carbon emission reduction level	Consumer green trust level	Consumer environment protection awareness	Consumer freshness preference	Others			
Ma et al. [39]	One supplier, one TPLSP, and one retailer	√	√	–	–	–	–	√	Revenue-and-cost-sharing contract	Y	N
Feng et al. [40]	One supplier and one retailer	√	√	–	–	–	–	–	Cost-sharing/revenue sharing and cost sharing/mixed coordination contract for cost-sharing and compensation strategies	N	N
Xie et al. [41]	One producer and one retailer	√	√	–	–	√	–	√	N	Y	N
Qin et al. [42]	One supplier and one retailer	√	√	–	–	–	–	√	Wholesale price contract and transfer payment	N	N
Yang and Yao [43]	One supplier and one retailer	√	√	√	–	√	√	–	Cost sharing contract and the two-part pricing contract	Y	N
Liao and Lu [44]	One producer, one supplier, and one retailer	√	–	–	–	–	–	√	Wholesale price/option contract	N	N
Wei and Huang [45]	One retailer and one manufacturer	√	–	–	–	–	–	√	Advance purchase discount contract and option contract	Y	Greening technology
Liu et al. [46]	One producer and one retailer	√	–	–	–	–	–	√	N	Y	Big data and blockchain
Yang et al. [47]	One supplier and one retailer	√	√	–	–	–	–	√	Revenue-sharing contract	N	N
Zhou et al. [48]	One agricultural cooperative and one supermarket	√	√	–	–	–	–	√	Two-part pricing contract	N	N
Jiang et al. [49]	One supplier and dual channel retailers	√	–	–	–	–	–	√	Cost-sharing contract	N	Blockchain
Liang and Hou [50]	One TPLSP and one retailer	√	√	–	–	–	–	√	Revenue-and-cost-sharing contract	N	N
This paper	One supplier, one TPLSP, and one retailer	√	√	√	√	√	√	–	“Revenue sharing + double cost sharing” and “two-part tariff + revenue sharing + double cost sharing” contract	Y	Blockchain

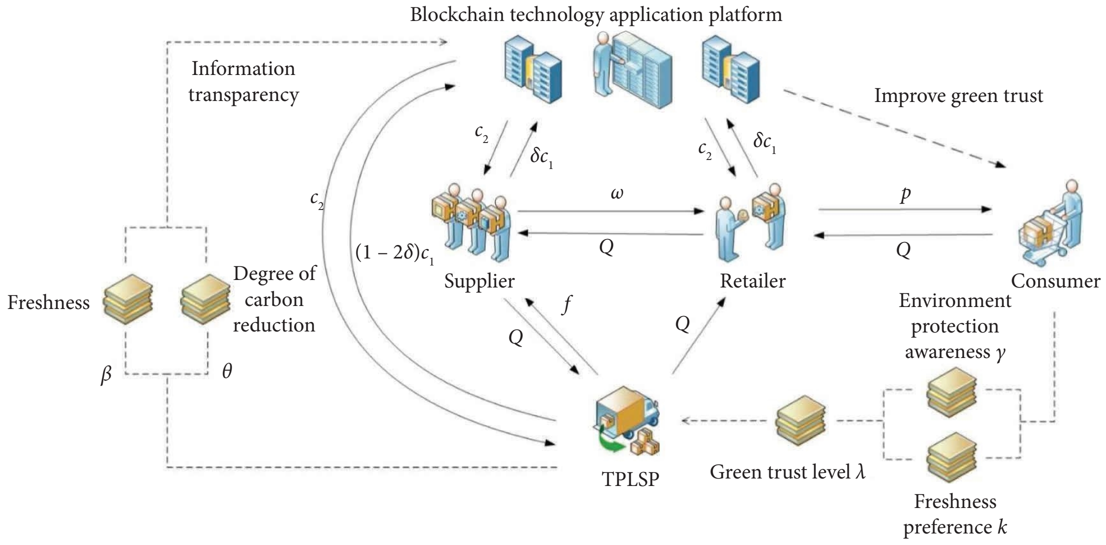


Figure 1: Operation model of fresh agricultural product supply chain based on blockchain technology.

3.2. Assumption. The relevant assumptions of this paper are as follows.

Assumption 1. The market information of the supplier and the retailer are completely symmetrical and the output of fresh products provided by the supplier is equal to the market demand, that is, the retailer does not have the problem of out-of-stock or inventory backlog.

Assumption 2. The market demand is simultaneously determined by the unit retail price of fresh products p, the carbon emission reduction level θ, the fresh-keeping effort level β, consumer environmental protection awareness γ, consumer freshness preference k, and consumer green trust level λ, $0 \leq \theta, \beta, \lambda \leq 1$. When no participant in the supply chain applies blockchain technology, the market demand functional form is $Q_1 = \alpha - p + \lambda\gamma\theta + \lambda k\beta$, while all participants in the supply chain apply blockchain technology; consumers can know the accurate carbon emission reduction level, product freshness, and other information, achieving a green trust level $\lambda = 1$, in which the market demand functional form is $Q_2 = \alpha - p + \gamma\theta + k\beta$.

Assumption 3. Investment in carbon emission reduction and fresh-keeping is a one-time investment which is not affected by demand. From existing literature, the quadratic cost function is widely used to describe the cost of carbon reduction and fresh-keeping. Therefore, the carbon emission reduction cost functional form in this paper is $C(\theta) = h\theta^2/2$ and the fresh-keeping cost functional form is $C(\beta) = b\beta^2/2$.

Assumption 4. In the supply chain enterprises' process of applying blockchain technology for information entry and traceability, the unit application cost of blockchain technology of the fresh product is c_1, and for each transaction process, the transaction cost saved per unit of fresh product is c_2. In the process of blockchain technology application, the application cost-sharing ratio of the supplier and the retailer is δ, and the ratio of blockchain technology application cost shared by TPLSP is $1 - 2\delta$, where $0 \leq \delta \leq 0.5$.

Assumption 5. To ensure a reasonable and feasible situation, we assume that $\alpha > c$, $c_1 < 3c_2 < c + c_1$, $hb > hk^2 + b\gamma^2$.

Assumption 6. In the following sections, we use π to represent the profits of the participants in the fresh agricultural product supply chain, the subscripts g, s, and t represent the supplier, the retailer, and the third-party logistics service provider, respectively, and the superscripts n, o, z, and d represent decentralized decision-making with or without the application of blockchain technology, centralized decision-making with or without the application of blockchain technology, respectively.

3.3. Notation. The notations involved in this paper and their meanings are shown in Table 2.

3.4. Model and Analysis. Considering the influence of factors such as the application cost of blockchain technology, environmental protection awareness, consumers' freshness preference, and green trust level, a three-stage game model consists of a supplier, a third-party logistics service provider, and a retailer is constructed. This paper first compares the decision-making and profits of the fresh agricultural product supply chain system under decentralized decision-making with and without the application of blockchain technology; for the situation where the benefits are higher, we analyze the supply chain participants' decisions and profits in the centralized decision-making mode. Based on such decisions and profits, the reason for the imbalance of the decentralized three-stage supply chain system is discussed, along with a reasonable and effective coordination contract formulated.

3.4.1. Decentralized Decision-Making Model When Blockchain Technology Is Not Applied. In the supply chain system

Table 2: List of notations.

Notation	Description
	Parameters
c	Unit production cost of fresh products
c_1	Unit application cost of blockchain technology of fresh products
c_2	After applying the blockchain technology, the transaction cost saved per unit of fresh products
h	Carbon emission reduction cost factor
b	Fresh-keeping cost factor
γ	Consumer environmental protection awareness
k	Consumer freshness preference
λ	Consumer green trust level, $0 \leq \lambda \leq 1$
α	Potential market scale
Q_1, Q_2	The fresh products demand when supply chain enterprises do not apply or apply blockchain technology
δ	The blockchain technology application cost-sharing ratio of supplier and retailer, $0 \leq \delta \leq 0.5$
η	The ratio of TPLSPs fresh-keeping costs shared by the supplier and the ratio of TPLSP carbon emission reduction costs shared by the retailer, $0 \leq \eta \leq 1$
φ	The ratio of revenue shared by the retailer to the supplier, $0 \leq \varphi \leq 1$
	Decision variables
ω	Unit wholesale price of fresh products
p	Unit retail price of fresh products
f	Unit service price of fresh products
θ	Carbon emission reduction level, $0 \leq \theta \leq 1$
β	Fresh-keeping effort level, $0 \leq \beta \leq 1$

under decentralized decision-making, each participant makes decisions with the ultimate goal of maximizing their own profits, which is a dynamic game process. First, the TPLSP takes its own profit maximization as the fundamental goal and determines the unit service price of fresh product f^n, carbon emission reduction level θ^n, and freshness preservation effort level β^n, which constitutes the first stage of the game; then, the supplier maximizes its own profit as the goal on the basis of TPLSP decision-making, determining the unit wholesale price w^n of fresh products, which constitutes the second stage; finally, the retailer decides to maximize its profits under the given f^n, θ^n, β^n, and w^n. In the decentralized decision-making supply chain model when blockchain technology is not applied, the profits functions of the retailer, the supplier, and theTPLSP are, respectively, as follows:

$$\pi_s^n = (p - \omega)(\alpha - p + \lambda\gamma\theta + \lambda k\beta), \tag{1}$$

$$\pi_g^n = (\omega - c - f)(\alpha - p + \lambda\gamma\theta + \lambda k\beta), \tag{2}$$

$$\pi_t^n = f(\alpha - p + \lambda\gamma\theta + \lambda k\beta) - \frac{1}{2}\left(h\theta^2 + b\beta^2\right). \tag{3}$$

Theorem 1. *In the decentralized decision-making model without the application of blockchain technology, the optimal unit service price of fresh products f^{n*}, the carbon emission reduction level θ^{n*}, the fresh-keeping effort level β^{n*}, the unit wholesale price w^{n*} of fresh product, the retail price p^{n*}, and optimal profits of each participant are as follows:*

$$\begin{aligned}
f^{n*} &= \frac{4(c-\alpha)hb}{\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb},\\
\theta^{n*} &= \frac{(c-\alpha)\lambda b\gamma}{\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb},\\
\beta^{n*} &= \frac{(c-\alpha)\lambda hk}{\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb},\\
\omega^{n*} &= \frac{c\lambda^2\left(hk^2 + b\gamma^2\right) - 2hb(3\alpha - c)}{\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb},\\
p^{n*} &= \frac{c\lambda^2\left(hk^2 + b\gamma^2\right) - hb(7\alpha - c)}{\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb},\\
\pi_s^{n*} &= \frac{[hb(\alpha - c)]^2}{\left(\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb\right)^2}\\
\pi_g^{n*} &= \frac{2[hb(\alpha - c)]^2}{\left(\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb\right)^2}\\
\pi_t^{n*} &= -\frac{(\alpha - c)^2 hb}{2\left(\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb\right)}.
\end{aligned} \tag{4}$$

3.4.2. Decentralized Decision-Making Model When Blockchain Technology Is Applied. In the decentralized supply chain decision-making model when applying blockchain technology, the game process of each participant is the same as when blockchain technology is not applied. The retailer, the supplier, and the TPLSP need to undertake a certain ratio of blockchain technology applications cost, but transaction costs can be reduced, consumers understand the freshness and emission reduction level of fresh products well through product traceability, and the consumer green trust level $\lambda = 1$. In this case, the profit functions of the retailer, the supplier, and the TPLSP are

$$\begin{aligned}
\pi_s^o &= \left(p - \omega - \delta c_1 + c_2\right)(\alpha - p + \gamma\theta + k\beta),\\
\pi_g^o &= \left(\omega - c - f - \delta c_1 + c_2\right)(\alpha - p + \gamma\theta + k\beta),\\
\pi_t^o &= \left[f - (1 - 2\delta)c_1 + c_2\right]Q_2 - \frac{1}{2}\left(h\theta^2 + b\beta^2\right).
\end{aligned} \tag{5}$$

Theorem 2. *In the decentralized decision-making model when applying blockchain technology, there exists the optimal unit service price of fresh product f^{o*}, carbon emission reduction level θ^{o*}, fresh-keeping effort level β^{o*}, the unit wholesale price w^{o*} of fresh product w^{o*}, the retail price p^{o*}, and optimal profit of each participant as follows:*

$$\begin{gathered} f^{o*} = \frac{4(c-\alpha)hb + c_1(1-2\delta)\left(hk^2 + b\gamma^2\right) + 4c_1(4\delta - 1)hb - c_2\left(hk^2 + b\gamma^2 + 4hb\right)}{hk^2 + b\gamma^2 - 8hb}, \\ \theta^{o*} = \frac{(c + c_1 - 3c_2 - \alpha)b\gamma}{hk^2 + b\gamma^2 - 8hb}, \\ \beta^{o*} = \frac{(c + c_1 - 3c_2 - \alpha)hk}{hk^2 + b\gamma^2 - 8hb}, \end{gathered} \tag{6}$$

$$\omega^{o*} = \frac{\left[c_1(1-\delta) + c - 2c_2\right]\left(hk^2 + b\gamma^2\right) - 2hb\left(3\alpha + c_1 - 4\delta c_1 + c + c_2\right)}{hk^2 + b\gamma^2 - 8hb} \tag{7}$$

$$\begin{gathered} p^{o*} = \frac{c_1\left(hk^2 + b\gamma^2\right) + (c - 3c_2)\left(hk^2 + b\gamma^2 - hb\right) - hb(7\alpha + c_1)}{hk^2 + b\gamma^2 - 8hb}, \\ \pi_s^{o*} = \frac{(c + c_1 - 3c_2 - \alpha)^2 h^2 b^2}{\left(hk^2 + b\gamma^2 - 8hb\right)^2}, \\ \pi_g^{o*} = \frac{2(c + c_1 - 3c_2 - \alpha)^2 h^2 b^2}{\left(hk^2 + b\gamma^2 - 8hb\right)^2}, \\ \pi_t^{o*} = -\frac{(c + c_1 - 3c_2 - \alpha)^2 hb}{2\left(hk^2 + b\gamma^2 - 8hb\right)}. \end{gathered} \tag{8}$$

Lemma 1

(i) $\theta^{o*} > \theta^{n*}$; $\beta^{o*} > \beta^{n*}$; $\pi_s^{o*} > \pi_s^{n*}$; $\pi_g^{o*} > \pi_g^{n*}$; $\pi_t^{o*} > \pi_t^{n*}$

(ii) *When* $\delta < (c_1 - c_2)(hk^2 + b\gamma^2) - A/2c_1$, $f^{o*} > f^{n*}$, *where* $A = 4hb(2\alpha - 2c + c_1 + c_2)$

(iii) *When* $\delta > (hk^2 + b\gamma^2)B - 2hb(c_1 + c_2)/c_1(hk^2 - 8hb + b\gamma^2)$, $\omega^{o*} < \omega^{n*}$, *where* $B = (c + c_1 - 2c_2 - c\lambda^2)$

(iv) *When* $hk^2 + b\gamma^2 > (3c_2 - c_1)hb/3c_2 - c + c_1 + c\lambda^2$, $p^{o*} > p^{n*}$, *on the contrary,* $p^{o*} < p^{n*}$

Lemma 1 demonstrates that compared with the situation where blockchain technology is not applied, when blockchain technology is applied, TPLSP will improve the carbon emission reduction level and fresh-keeping efforts and the optimal profits of the retailer, the supplier, and the TPLSP will increase; when the blockchain technology application cost-sharing ratio of the supplier and the retailer is lower than a certain value, that is, when the ratio of blockchain technology application cost that TPLSP undertakes is high enough, TPLSP will increase the service price to ensure that its own interests are protected; when the cost-sharing ratio of blockchain technology application is higher than a certain value, the service price given by the supplier to the TPLSP will be significantly reduced, and the wholesale price given by the retailer to the supplier will also be reduced. In order to maximize their own profits, the retailer will reduce retail prices to increase market demand; when environmental protection awareness and freshness preference are higher than a certain value, with a high market demand caused by consumers' green trust level reaching 1 due to the application of blockchain technology, the retailer can increase price appropriately. On the contrary, if environmental protection awareness and freshness preference are low, the retailer can only increase market demand by reducing the retail price because of information transparency.

3.4.3. Centralized Decision-Making Model When Blockchain Technology Is Applied. Under the centralized decision-making model, participants in the supply chain take the maximization of system profits as the fundamental goal to make a unified decision as a whole on the level of carbon emission reduction, the fresh-keeping effort level, and the unit retail price of fresh products. Since Lemma 1 has proved that the retailer, the supplier and the TPLSP have higher profits when applying blockchain technology; that is, the total profits of the supply chain system are higher; so this paper considers the centralized decision-making of supply chain enterprises when applying blockchain technology, and the total profits of the fresh agricultural product supply chain is as follows:

$$\pi^z = \left[p - c - c_1 + 3c_2\right]Q_2 - \frac{1}{2}\left(h\theta^2 + b\beta^2\right). \tag{9}$$

Theorem 3. *In the centralized decision-making model when applying blockchain technology, the optimal carbon emission reduction level* θ^{z*}, *fresh-keeping effort level* β^{z*}, *unit retail price of fresh product* p^{z*}, *and total profits of the supply chain are as follows:*

$$\begin{aligned}
\theta^{z*} &= \frac{(c + c_1 - 3c_2 - \alpha)b\gamma}{hk^2 + b\gamma^2 - 2hb},\\
\beta^{z*} &= \frac{(c + c_1 - 3c_2 - \alpha)hk}{hk^2 + b\gamma^2 - 2hb},\\
p^{z*} &= \frac{C - hb\left(\alpha + c + c_1 - 3c_2\right)}{hk^2 + b\gamma^2 - 2hb},\\
\pi^{z*} &= -\frac{(c + c_1 - 3c_2 - \alpha)^2 hb}{2\left(hk^2 + b\gamma^2 - 2hb\right)},
\end{aligned} \tag{10}$$

where $C = (c + c_1 - 3c_2)(hk^2 + b\gamma^2)$.

Lemma 2. $p^{z*} < p^{o*}$; $\theta^{z*} > \theta^{o*}$; $\beta^{z*} > \beta^{o*}$; $\pi^{z*} > \pi_s^{o*} + \pi_g^{o*} + \pi_t^{o*}$.

Lemma 2 demonstrates that when applying blockchain technology, the retail price of fresh products under centralized decision-making is lower than the optimal price under decentralized decision-making, but the carbon emission reduction level and fresh-keeping effort level of TPLSP are higher than those of decentralized decision-making, and the total profits of the supply chain under centralized decision-making is higher than the sum of the optimal profits of the retailer, the supplier, and TPLSP under decentralized decision-making. This is because, in the centralized decision-making mode, the retailer chooses to reduce retail prices with the goal of maximizing the overall profits of the supply chain. Since consumers can trace the source of products using the blockchain technology, carbon emission reduction information and fresh-keeping information are both transparent. Therefore, TPLSP will promote environmental protection awareness and freshness preference by improving the level of carbon emission reduction and fresh-keeping effort, which will significantly increase the market demand for fresh products, resulting in the optimal profits increase of the three-stage supply chain system composed of the retailer, the supplier, and the TPLSP.

Lemma 3

(i) *f^{o*} and ω^{o*} increase with the increase of transaction cost saved by the application of blockchain technology, consumers' environmental protection awareness, and freshness preference and decrease with the increase of unit production cost of fresh products, carbon emission reduction factor, and fresh-keeping cost factor. When $\delta < hk^2 + b\gamma^2 - 4hb/hk^2 + b\gamma^2 - 16hb$, f^{o*} increases with the increase of the application cost of blockchain technology and vice versa; when $\delta > hk^2 + b\gamma^2 - 2hb/hk^2 + b\gamma^2 - 8hb$, ω^{o*} decreases with the increase of the application cost of blockchain technology and vice versa.*

(ii) *p^{o*} and p^{z*} increase with the increase of the unit production cost of fresh products, the application cost of blockchain technology, consumers' environmental protection awareness, and freshness preference and decrease with the increase of the transaction cost, carbon emission reduction cost factor, and fresh-keeping cost factor.*

(iii) *θ^{o*}, θ^{z*}, β^{o*}, and β^{z*}, along with the profits of each participant under decentralized decision-making and the total profits of the system under centralized decision-making decrease with the increase of the unit production cost of fresh products, application cost of blockchain technology, carbon emission reduction cost factor, and fresh-keeping cost factor, increase with the increase of the transaction cost savings of applying blockchain technology, consumers' environmental protection awareness, and freshness preference.*

Lemma 3 demonstrates that when the blockchain technology application cost-sharing ratio of the supplier and the retailer is higher than a certain value, with the increase of blockchain technology application costs, the retailer is more reluctant to pay the higher wholesale price to the supplier, resulting in a lower service price paid to the TPLSP by the supplier. In any case, due to the increase in the unit production cost of fresh products, the application cost of blockchain technology, and the reduction of transaction cost saved by the application of blockchain technology, to ensure that their own profits are protected, the retailer will increase retail prices and the TPLSP will reduce carbon emission reduction and fresh-keeping effort level. Similarly, if the carbon emission reduction cost factor and the fresh-keeping cost factor increase, the TPLSP will choose to reduce the carbon emission reduction level and the fresh-keeping effort level for the purpose of maximizing its own profits, causing negative effects such as reducing consumers' environmental protection awareness, freshness preference, and market demand. The retailer will maximize their own benefits by lowering the retail price and increasing demand; however, the inevitable reduction of market demand will still damage the profits of the retailer, the supplier, and the TPLSP in the supply chain. On the contrary, the improvement of consumers' environmental protection awareness and freshness preference will increase market demand, and the retailer can appropriately increase the retail price and are more willing to pay the higher wholesale price to the supplier, which will also increase the service price obtained by the TPLSP.

3.5. Coordinating the Supply Chain.

Under the situation of decentralized decision-making applying the blockchain technology, due to the contradiction between the individual profits and the system profit, the decision-making in the supply chain cannot reach an optimal condition, resulting in damage to the overall profits of the supply chain. Through effective contract coordination, the TPLSP can be willing to reach the carbon emission reduction level and fresh-keeping effort level under the centralized decision-making, resulting in higher economic profits for supply chain enterprises and the system than the optimal level under decentralized decision-making, achieving a Pareto improvement. Therefore, this paper designs a contract incentive mechanism to coordinate the supply chain system.

3.5.1. "Revenue Sharing + Double Cost Sharing" Contract. In order to motivate the retailer to increase their order quantity, the supplier can first give the retailer a wholesale price discount ω^{d*}; meanwhile, to make up for the supplier price loss, the retailer can return a ratio φ of the sales revenue to the supplier; by sharing a ratio η of the TPLSP fresh-keeping cost can the supplier improve the freshness of fresh products, thereby attracting the retailer to order more products. At the same time, the TPLSP should provide the supplier with a service price discount to maintain a long-term cooperative relationship between the two parties. Finally, the retailer as the direct beneficiaries of the increased demand for fresh products should share the carbon emission reduction costs of the TPLSP in order to motivate them to make greater emission reduction efforts. Under this contract, the profit functions of the retailer, the supplier, and the TPLSP are as follows:

$$\pi_s^d = (1-\varphi)(p-\omega-\delta c_1+c_2)Q_2-\frac{1}{2}\eta h\theta^2, \tag{11}$$

$$\pi_g^d = [\varphi p+(1-\varphi)\omega-c+(1+\varphi)(c_2-\delta c_1)-f]Q_2-\frac{1}{2}\eta b\beta^2, \tag{12}$$

$$\pi_t^d = \frac{[f-(1-2\delta)c_1+c_2]Q_2-(1-\eta)\left(h\theta^2+b\beta^2\right)}{2}. \tag{13}$$

Theorem 4. *Under the contract of "revenue sharing + double cost sharing," there are optimal unit service price of fresh product f^{d*}, carbon emission reduction level θ^{d*}, fresh-keeping effort level β^{d*}, wholesale price w^{d*}, retail price of fresh product p^{d*}, and optimal profit of each participant are as follows:*

$$f^{d*} = \frac{D+2hb[(\alpha-c)(1-\varphi)+E]}{hk^2+b\gamma^2-2hb}, \tag{14}$$

where $D=(c_1-2\delta c_1-c_2)(hk^2+b\gamma^2)$ and $E=c_1(2\delta+\varphi-2)+c_2(4-3\varphi)$;

$$\omega^{d*} = c+c_1-\delta c_1-2c_2, \tag{15}$$

$$\pi_s^{d*} = -\frac{hbC\left[2(\varphi-1)h+\eta\gamma^2\right]}{2\left(hk^2+b\gamma^2-2hb\right)^2}, \tag{16}$$

$$\pi_g^{d*} = -\frac{hbC\left[2(\varphi-2)b+\eta k^2\right]}{2\left(hk^2+b\gamma^2-2hb\right)^2}, \tag{17}$$

$$\pi_t^{d*} = \frac{F\left[4(\varphi-1)hb+\left(hk^2+b\gamma^2\right)(\eta-1)\right]}{2\left(hk^2+b\gamma^2-2hb\right)^2}, \tag{18}$$

where $F=(c+c_1-3c_2-\alpha)^2hb$.

Lemma 4

(1) *The optimal profits of the supply chain system after the "revenue sharing + double cost sharing" contract coordination is equal to the optimal profits under the centralized decision-making mode*

(2) *When $0<\varphi\le\varphi_1$, $0<\eta\le 1$ or $\varphi_1<\varphi<\varphi_2$, $0<\eta<\eta_1$, and $\pi_s^{d*}>\pi_s^{o*}$; when $0<\varphi<1$, $0<\eta<1$, and $\pi_g^{d*}>\pi_g^{o*}$; when $0<\varphi<1$, $0<\eta<1$, and $\pi_t^{d*}<\pi_t^{o*}$*

$$\begin{aligned}\varphi_1 &= \frac{24h^3b\left(k^2-5b\right)+h^2\gamma^2\left(k^4-16k^2b+88b^2\right)+G}{2h\left(hk^2+b\gamma^2-8hb\right)^2}, \text{ where } G=b\gamma^4\left(2hk^2-16hb+b\gamma^2\right),\\ \varphi_2 &= -\frac{12hb\left(2hk^2-5hb+b\gamma^2\right)}{\left(hk^2+b\gamma^2-8hb\right)^2};\ \eta_1=-\frac{H+12hb\left(hk^2-5hb+b\gamma^2\right)}{\left(hk^2+b\gamma^3-8hb\right)^2}, \text{ where } H=2h\left[\varphi\left(hk^2-8hb+b\gamma^2\right)\right]^2.\end{aligned} \tag{19}$$

Lemma 4 demonstrates that after the coordination of the "revenue sharing + double cost sharing" contract, the total profits of the supply chain system is equal to the optimal profits of the system under centralized decision-making and the contract can improve the optimal profits of the retailer and the supplier. However, it reduces the optimal profit of the TPLSP, which is mainly because the service price given by the supplier to the TPLSP will be significantly reduced. Therefore, the TPLSP could not maximize its own profits and will decline such a contract. It can be seen that the contract of "revenue sharing + double cost sharing" alone cannot achieve the coordination of the supply chain.

3.5.2. "Two-Part Tariff + Revenue Sharing + Double Cost Sharing" Contract. It can be seen from Lemma 4 that the contract of "revenue sharing + double cost sharing" can coordinate the total profits of the supply chain system and improve the optimal profits of the retailer and the supplier, but it will reduce the optimal profits of the TPLSP. Therefore, in this section, we add a "Two-part tariff" to the "revenue sharing + double cost sharing" contract; that is, the retailer and the supplier need to pay a certain amount of fixed fees T_1 and T_2 to the TPLSP, respectively, so as to realize Pareto improvement of the economic profits of all participants and a coordinated supply chain system, where the following theorems can be obtained.

Lemma 5. *When φ, η, T_1, and T_2 meet the following conditions, the three-stage fresh agricultural product supply chain can achieve perfect coordination:* $0 < \varphi \leq \varphi_1$, $0 < \eta \leq 1$ *or* $\varphi_1 < \varphi < \varphi_2$, $0 < \eta < \eta_1$, $0 < T_1 < \min\{T_{11}, T_{12}\}$, *and* $T_{22} < T_2 < T_{21}$.

$$\begin{aligned} T_{11} &= \frac{IJb + 24h^2b\left(hk^2 + b\gamma^2 - 5hb\right) + M}{2\left(hk^2 + b\gamma^2 - 8hb\right)^2\left(hk^2 + b\gamma^2 - 2hb\right)^2}; T_{12} = \frac{-IM - \left(hk^2 + b\gamma^2\right)\left(hk^2 + b\gamma^2 - 8hb\right)\eta}{2\left(hk^2 + b\gamma^2 - 8hb\right)^2\left(hk^2 + b\gamma^2 - 2hb\right)^2}; \\ T_{21} &= \frac{IJh + 48hb^2\left(hk^2 + b\gamma^2 - 5hb\right) + k^2L}{2\left(hk^2 + b\gamma^2 - 8hb\right)^2\left(hk^2 + b\gamma^2 - 2hb\right)^2}; T_{22} = \frac{\left(h^3k^2 + b^3\gamma^2\right)K + h^3b^3N + h^3k^2T_1O + P + V}{2\left(hk^2 + b\gamma^2 - 8hb\right)^2\left(hk^2 + b\gamma^2 - 2hb\right)^2}, \end{aligned} \tag{20}$$

where $I = (c + c_1 - 3c_2 - \alpha)^2 hb$, $J = [2\varphi h(hk^2 + b\gamma^2 - 2hb)]^2$, $K = \varphi h^2 b^2 (36c_2^2 - 24c_1c_2 + 4c_1^2)$, $L = \eta(hk^2 + b\gamma^3 - 8hb)^2$, $M = 4hb[\varphi h(k^2 - 8b) + 9hb + \varphi b\gamma^2]$, $N = (324 - 288\varphi)c_2^2 + -64T_1(192\varphi - 216)c_1c_2 + (36 - 32\varphi)c_1^2$, $O = 2k^4 - 24bk^2 + 72b^2$, $P = 6h^2bT_1\gamma^2(k^4 - 8k^2b + 24b^2)$, $R = 3hk^2 - 12hb + b\gamma^2$, $S = (\alpha - c)^2 - 2(c + \alpha)(3c_2 - c_1)$, $U = \eta(-hk^2 + 8hb - b\gamma^2)(hk^2 + b\gamma^2)$, *and* $V = 2b^2T_1\gamma^4R + hbKS - IU$.

Lemma 5 demonstrates that when the parameters of the "two-part tariff + revenue sharing + double cost sharing" contract are controlled within a feasible threshold, the three-stage fresh agricultural product supply chain system can achieve perfect coordination.

4. Results

In order to further verify the effectiveness and practicability of various decisions, profits factors, and coordination contracts in the three-stage fresh agricultural product supply chain constructed mentioned above, this paper uses Matlab2021a software to simulate and analyze relevant parameters. Without loss of generality, under the condition that the model assumptions and the Hessian matrix results are satisfied, the parameter value range is set, and the parameter assignments of the literature [35] are referenced, assuming $\alpha = 10$, $c = 2$, $c_2 = 0.5$, $h = 20$, $b = 20$, $\varphi = 0.2$, and $\eta = 0.3$.

4.1. Analysis of Influencing Factors of Supply Chain System Decision and Profit

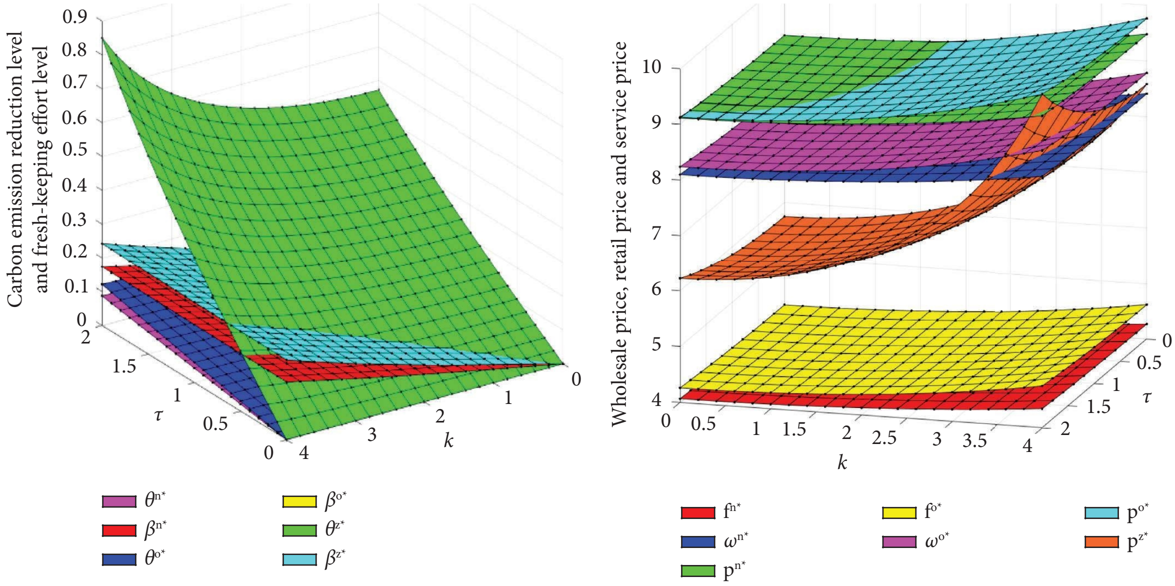
4.1.1. Consumer Environmental Protection Awareness and Freshness Preference. In order to more intuitively show the influence of consumer environmental protection awareness and freshness preference on the decision-making of the supply chain system, on the basis of the above parameter assignments, set $c_1 = 1$, $\delta = 0.3$, and $\lambda = 0.8$, the obtained results are shown in Figures 2(a) and 2(b).

As shown in Figures 1 and 2, in any decision-making mode, each decision variable will increase with the improvement of environmental protection awareness and freshness preference, but the environmental protection awareness has a lower impact on the fresh-keeping effort level, and freshness preference has a lower impact on carbon emission reduction level. When consumers' environmental protection awareness and freshness preference are low, under decentralized decision-making, the optimal retail price when blockchain technology is applied is lower than the optimal price when blockchain technology is not applied and vice versa; when consumers' environmental protection awareness and freshness preference are higher than a certain value, the retail price of applying blockchain technology under decentralized decision-making is the highest, which is in line with the conclusions of Lemmas 1(iv) and 2. The optimal value of each decision variable is the highest in the centralized decision-making mode, the second is the application of blockchain technology under decentralized decision-making, and the lowest when blockchain technology is not applied, which shows that the application of blockchain technology can improve the economic profits of the supply chain system.

4.1.2. Consumer Green Trust Level, Blockchain Technology Application Cost, and Sharing Ratio. In order to more intuitively show the impact of green trust level, blockchain technology application cost, and sharing ratio on the decision-making and profits of the supply chain system, the same as the above-given parameter assignment, the obtained results are shown in Figures 3(a)–3(e).

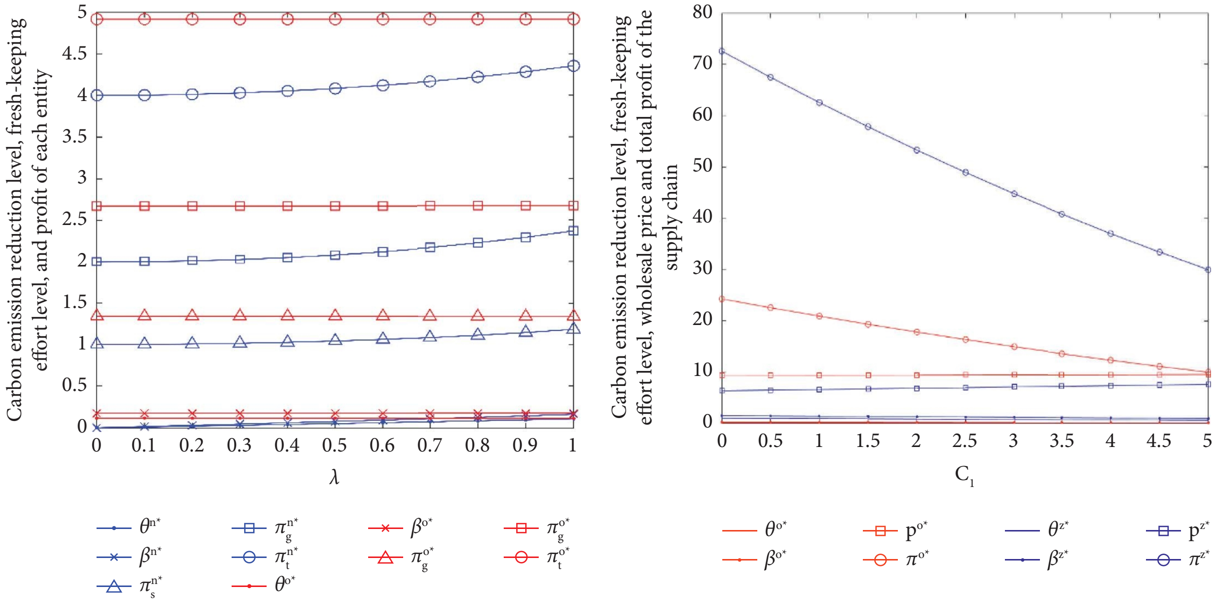
As can be seen from Figure 3(a), the optimal carbon emission reduction level, fresh-keeping effort level, and the profits of each participant are positively correlated with the green trust level of consumers when the blockchain technology is not applied under decentralized decision-making. When the blockchain technology is applied, the consumer green trust level is 1, so θ^{o*}, β^{o*}, π_s^{o*}, π_s^{o*}, and π_t^{o*} have nothing to do with λ and are higher than the optimal results when the blockchain technology is not applied; as can be seen from Figure 3(b), the optimal carbon emission reduction level, fresh-keeping effort level, and supply chain system profits when applying blockchain technology are all negatively correlated with the application cost of blockchain technology, but the retail price is positively correlated with it, and the optimal carbon emission reduction level, fresh-keeping effort level, and total profits of the supply chain system under centralized decision-making are higher, and the retail price is lower.

Figure 3(d) shows that when the blockchain technology application cost-sharing ratio of the supplier and the retailer is less than a certain value, f^{o*} and ω^{o*} increase with the increase of c_1. On the contrary, when the blockchain technology application cost-sharing ratio of the TPLSP is



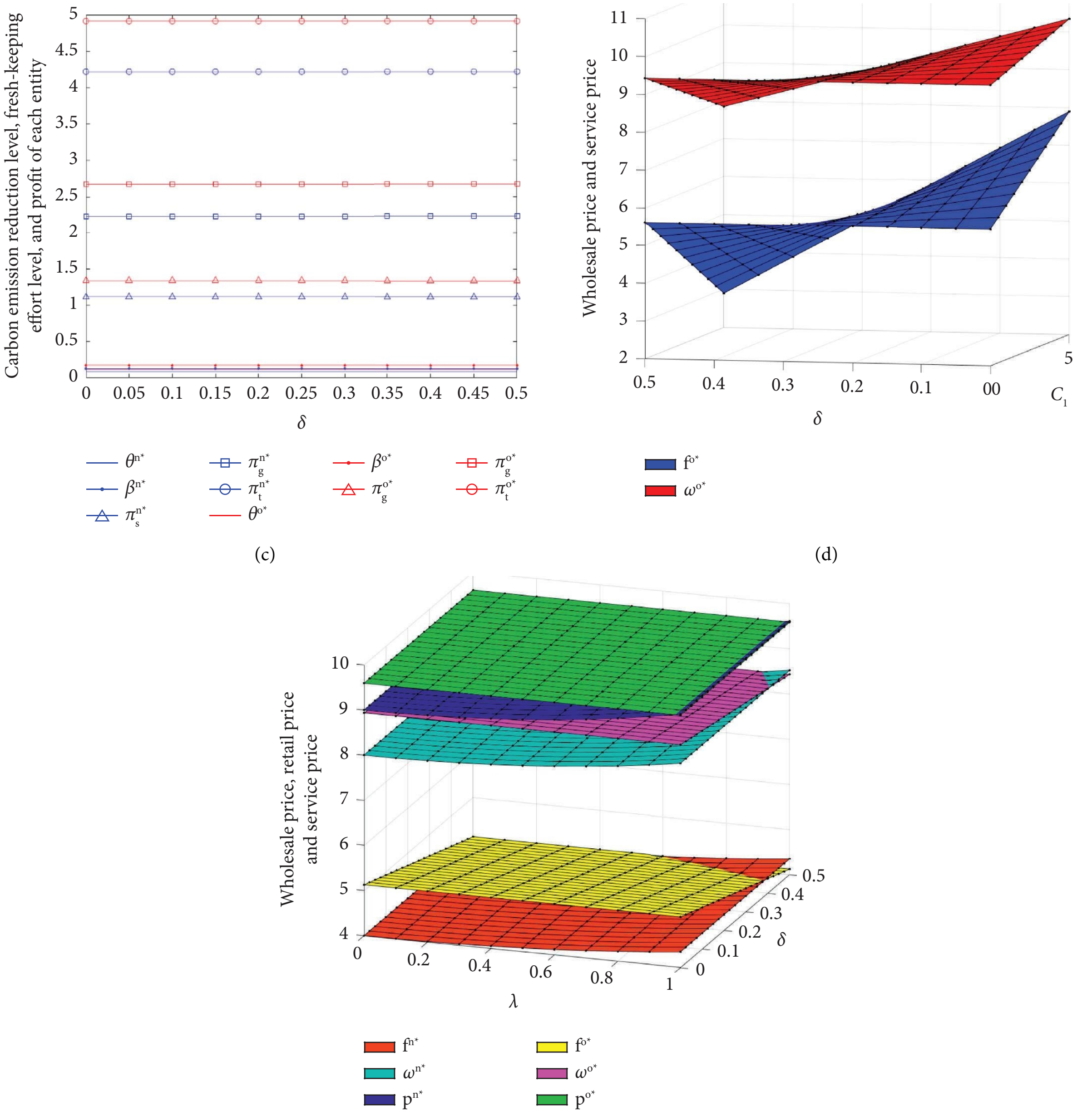
(a) (b)

Figure 2: Effects of γ and k on supply chain system decisions.



(a) (b)

Figure 3: Continued.



(c)

(d)

(e)

FIGURE 3: Effects of λ, c_1, and δ on supply chain system decisions and profits.

less than a certain value, f^{o*} and ω^{o*} decrease with the increase of c_1, which is consistent with the conclusion of Lemma 3(i). This shows that the supplier and the TPLSP will make corresponding adjustments to their own decisions according to the changes in the application cost of blockchain technology. Therefore, as shown in Figure 3(c), the optimal carbon emission reduction level, fresh-keeping effort level, and the profits of each participant have nothing to do with δ under decentralized decision-making.

As can be seen from Figure 3(e), when the blockchain technology is not applied, the unit wholesale price and service price of fresh products are positively correlated with the green trust level, and when the supplier's blockchain technology application cost-sharing ratio is greater than a certain value, $f^{n*} > f^{o*}$, $\omega^{n*} > \omega^{o*}$, and $p^{n*} > p^{o*}$, it is consistent with the conclusions of Lemmas 1(ii)–1(iv). This shows that when δ is high, the TPLSP only needs to pay a lower application cost of blockchain technology, and from the perspective of maximizing the overall profits of the supply chain, the service price will be reduced. Therefore, the supplier will also reduce the wholesale price so that the retailer can sell fresh products at lower prices, thereby increasing market demand and improving system economic profits.

4.2. *The Impact of Coordination Contracts on Supply Chain System Decisions and Profits*

4.2.1. "Revenue Sharing + Double Cost Sharing" Contract. Figure 4(a) depicts the impact of the "revenue sharing + double cost sharing" contract on wholesale prices and service prices as the unit production cost of fresh products changes. It can be seen from the figure that the wholesale price and service price after contract coordination are lower than the optimal decision results under centralized decision-making, which shows that in order to make the retailer reduce retail prices and increase market demand, both f and ω are significantly lower, and $f^{d*} < 0$ means that the TPLSP not only does not charge service prices but also gives certain subsidies to the supplier. As shown in Figure 4(b), the maximum profits of the retailer and the supplier after contract coordination is higher than the optimal result under decentralized decision-making. The maximum profits of the TPLSP are lower than the optimal result under decentralized decision-making, and the profits of the TPLSP increase with the increase of the production cost of fresh products, while the profits of the supplier and the retailer decrease with the increase of production cost.

Figure 4(c) depicts the trend of changes in the ratio of fresh-keeping costs shared by the supplier, the ratio of carbon emission reduction costs shared by the retailer, and the ratio of revenue shared by the retailer with the change of carbon emission reduction costs. Substitute φ_1 and φ_2 into η_1 to get η_{11} and η_{12}, as shown in the figure; there are always $\varphi_1 < \varphi_2$, $\eta_{11} = 1$, and $\eta_{12} \approx 0$; that is, when $0 < \varphi \leq \varphi_1$ and $0 < \eta < \eta_{11} = 1$ and when $\varphi_1 < \varphi < \varphi_2$ and $0 < \eta < \eta_{12} = 0$. This means that if the ratio of revenue shared by the retailer is higher than a certain value, they will not share the carbon emission reduction cost of the TPLSP, so that the TPLSP will not give service price discounts to the supplier so that the supplier will also not share the TPLSP fresh-keeping cost. The contract eventually evolved into a "wholesale price + revenue sharing" contract between the retailer and the supplier, which can also explain why the contract can improve the profits of the retailer and the supplier but will hurt the profits of the TPLSP. Therefore, the perfect coordination of the supply chain system cannot be achieved only through the contract of "revenue sharing + double cost sharing."

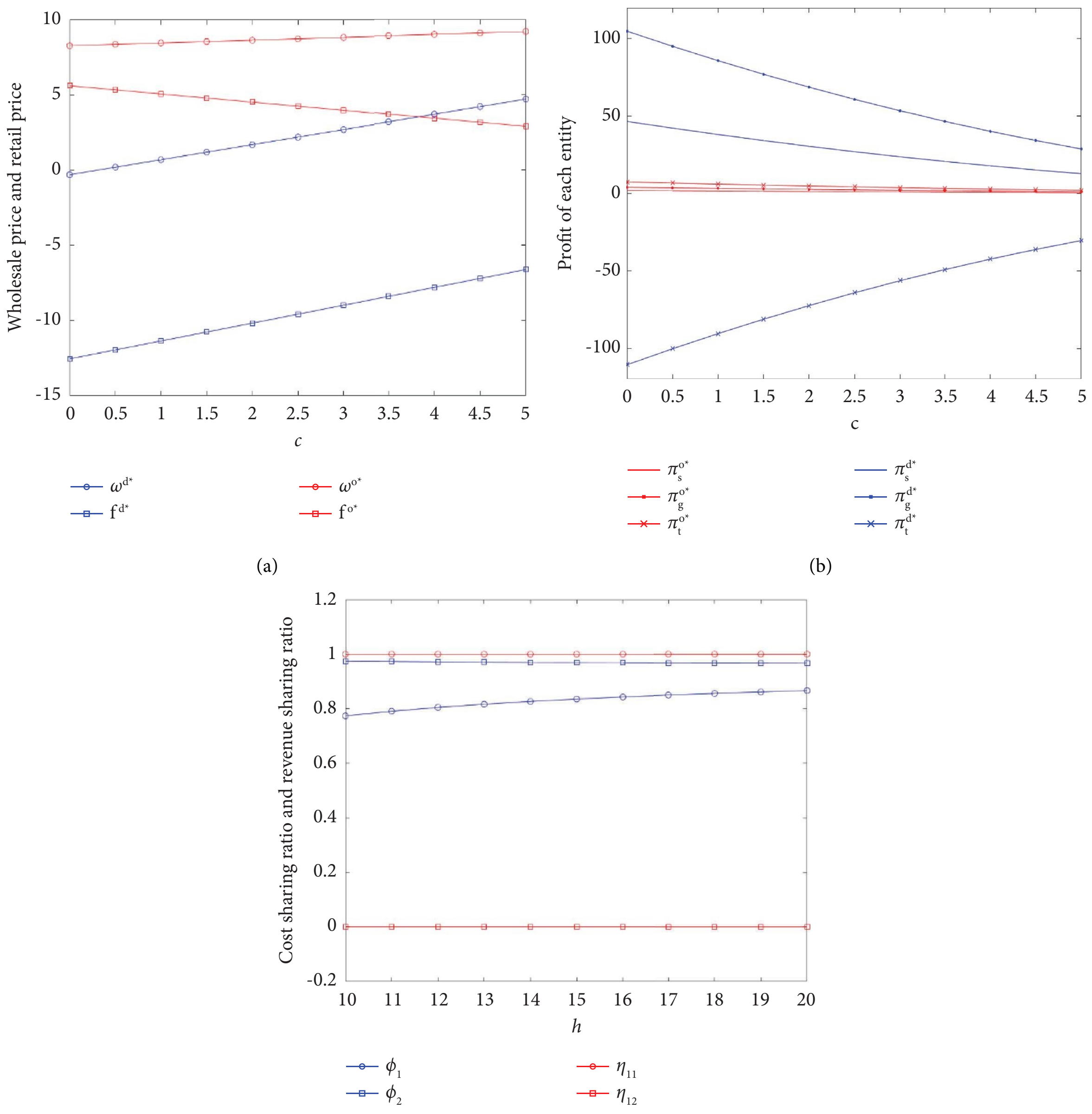
4.2.2. "Two-Part Tariff + Revenue Sharing + Double Cost Sharing" Contract. Figure 5(a) depicts the changing trends of T_1 and T_2 with carbon emission reduction costs in the contract of "two-part tariffs + revenue sharing + double cost sharing." Substitute T_{11} and T_{12} into T_{22} to get T_{22}^1 and T_{22}^2, As shown in the figure, there are always, $T_{12} > T_{11}$ and $T_{21} > T_{22}^1 > T_{22}^2$. Therefore, the feasible conditions of the coordination contract are: $0 < T_1 < T_{11}$ and $T_{22}^1 < T_2 < T_{21}$, which is consistent with the conclusion of Lemma 5. Figures 5(b)–5(d) describe the effects of T_1 and T_2 on the profits of each participant in the supply chain system. After contract coordination, the retailer's profits increase with the decreases of T_1, and the supplier's profits increase with the decreases of T_2, and the TPLSP's profits increase with the increases of T_1 and T_2. In the case of parameter setting in this paper, as shown in the figure, when $T_1 < 29.2416$ and $\pi_s^{d*} > \pi_s^{o*}$, when $T_2 < 66.0408$ and $\pi_g^{d*} > \pi_g^{o*}$, and when $T_1 > 15$ and $T_2 > 47$, $\pi_t^{d*} > \pi_t^{o*}$. Therefore, when $15 < T_1 < 29.2416$ and $47 < T_2 < 66.0408$, always have $\pi_s^{d*} \geq \pi_s^{o*}$, $\pi_g^{d*} \geq \pi_g^{o*}$, and $\pi_t^{d*} \geq \pi_t^{o*}$. That is, the contract of "two-part tariff + revenue sharing + double cost sharing" can realize the Pareto improvement of the profits of each participant in the three-stage fresh agricultural product supply chain system and achieve perfect coordination.

5. Managerial Insights and Practical Implications

5.1. Practical Implications. Fresh agricultural products are not easy to store and have strong timeliness. During transportation and storage, they have high requirements for refrigeration technology and thermal insulation technology, resulting in a very high level of carbon emissions in circulation. With the improvement of consumers' freshness preference and environmental protection awareness and the country's emphasis on carbon emissions, enterprises at each node of the fresh agricultural product supply chain must not only consider improving freshness to increase economic profits but also consider the social responsibility of low-carbon emission reduction. The application of blockchain technology can enable consumers to understand the real fresh-keeping information and emission reduction information of enterprises, improve consumers' green trust level, and then expand the market demand for fresh agricultural products. Therefore, based on the dual perspectives of blockchain and low carbon, this paper considers factors such as the fresh-keeping cost, carbon emission reduction cost, and the blockchain technology application cost-sharing ratio into the research on the coordination of the fresh agricultural products supply chain. By comparing the optimal decision-making and profit of the supply chain under the three decision-making modes, this paper provides a reliable theoretical reference for the application of blockchain technology in the supply chain. By designing a reasonable coordination contract, we can achieve a cooperative relationship between enterprises in the supply chain and finally achieve the optimal overall efficiency of the supply chain and the Pareto improvement of the profits of each participant and also further encourage the third-party logistics service providers to make the greatest efforts to freshness-keeping and carbon emission reduction in transportation and storage. Therefore, this research has important practical significance for the economic development and ecological civilization construction of the whole society.

5.2. Managerial Insights. On the basis of the practical implications mentioned above, the management implications of this paper can be concluded as follows:

(1) Environmental protection awareness and freshness preference are important factors to motivate enterprises in the supply chain of fresh agricultural products to produce, transport, and sell. Enterprises can use media such as radio and television to vigorously



(a)

(b)

(c)

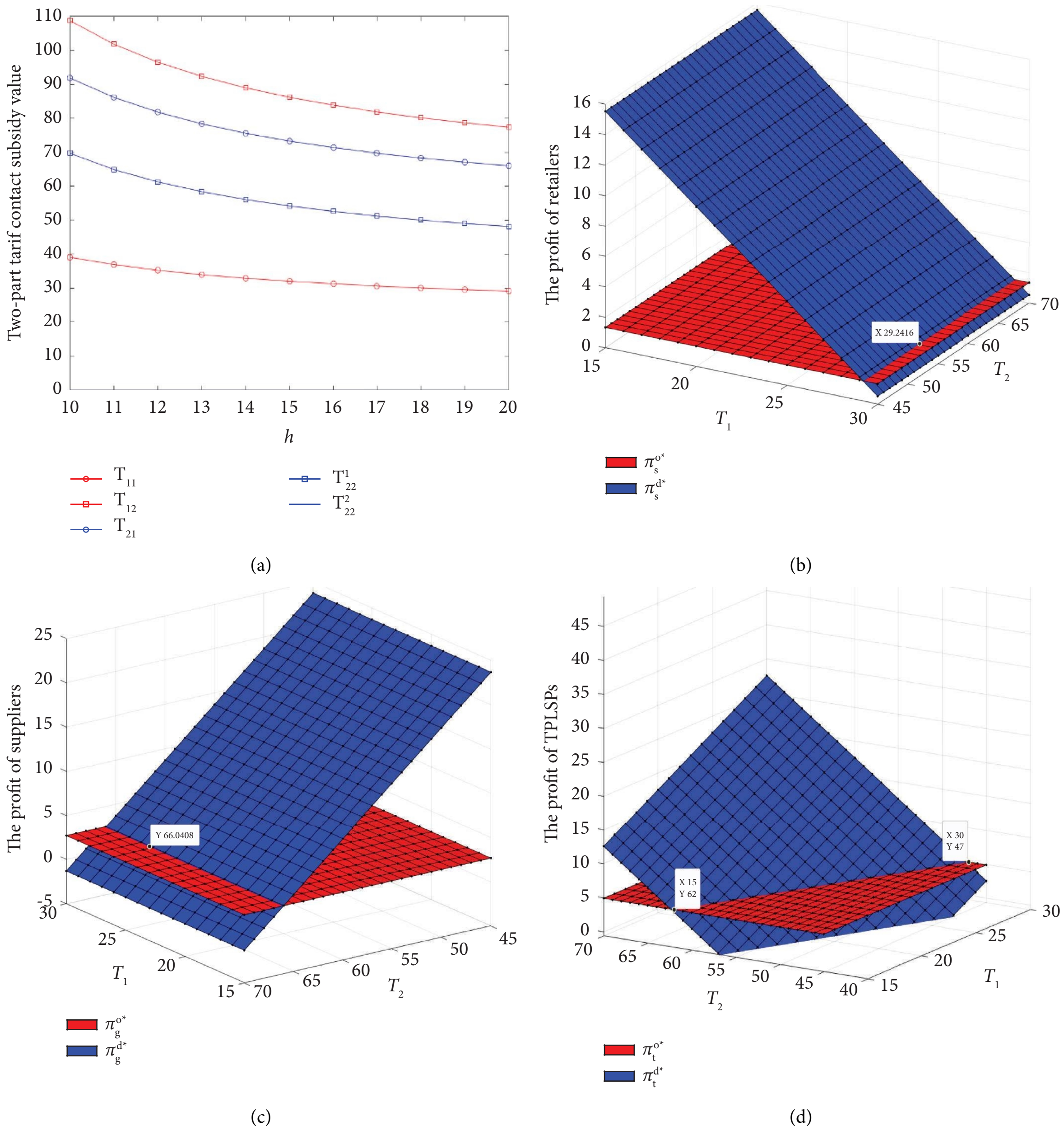
FIGURE 4: "Revenue sharing + double cost sharing" contract change trend and its impact on profits.

publicize the concept of sustainable development and encourage consumers to form a low-carbon and green consumption concept. The government can consider giving corresponding price subsidies to fresh agricultural products with low-carbon delivery and high freshness to meet people's demand for high-quality dairy products and logistic services.

(2) The green trust level plays a decisive role in whether consumers buy fresh and low-carbon fresh agricultural products. Enterprises in the supply chain should apply blockchain technology to ensure emission reduction and transparency of fresh-keeping information to improve consumers' green trust level and expand the supply of high-quality fresh agricultural products.

(3) Enterprises in the fresh agricultural product supply chain applying blockchain technology should reasonably decide the cost-sharing ratio, subsidies are given by the government to reduce the cost of blockchain technology application, so as to increase the carbon emission reduction level, the fresh-keeping effort level, and the profits of various participants, thereby ensuring the quality and safety of fresh products and achieving carbon peaking and carbon neutrality for fresh agricultural products.

(4) Under the decentralized decision-making mode in the supply chain system, the optimal profit of TPLSPs is always higher than the maximum profit of suppliers and retailers. Therefore, TPLSPs can be the organization enterprises for the contract



(a)

(b)

(c)

(d)

Figure 5: “Two-part tariff + revenue sharing + double cost sharing” contract change trend and its impact on profits.

coordination mechanism of “two-part tariff + revenue sharing + double cost sharing,” lead suppliers and retailers to coordinate according to the agreement, so that the tripartite decision-making participant can obtain greater profits and play a positive role in promoting the stable development of the fresh agricultural product supply chain, the improvement of people’s quality of life, and the construction of a pleasant ecological environmental.

6. Conclusions and Outlook

6.1. Conclusions. This paper studies a three-stage fresh agricultural product supply chain system consisting of a supplier, a third-party logistics service provider (TPLSP), and a retailer, in which fresh products have no fixed shelf life, and market demand is influenced by factors such as retail price, consumer environmental protection awareness, freshness preference, and green trust level. Comparative analysis of the optimal decision-making, profits of each enterprise under decentralized decision-making without the application of blockchain technology, decentralized decision-making with blockchain technology, and centralized decision-making with blockchain technology. Analysis of the influence of factors such as consumers’ environmental protection awareness, freshness preference, green trust level, blockchain technology application cost, and sharing ratio on the decision-making and profits of the supply chain system. Also, the coordination effect of the contract of “revenue sharing + double cost sharing” and the contract of “two-part tariff + revenue sharing + double cost sharing" on the three-stage supply chain system are discussed. Finally, the correctness of the theoretical model and the feasibility of the coordination contract are verified through the simulation analysis of an example. The research conclusions of this paper mainly include the following theories:

(1) Optimal wholesale price, retail price, service price, optimal carbon emission reduction level, fresh-keeping effort level, and the profits of each participant are positively correlated with consumer green trust level when blockchain technology is not applied. Although the application of blockchain technology will increase the cost of enterprises, it will also reduce transaction costs and make consumer green trust level to 1, thereby increasing the market demand. Therefore, the profits of each participant of the supply chain have been improved.

(2) When the blockchain technology application cost-sharing ratio by the supplier and the retailer is high, the wholesale price, service price, and retail price will be lower than the optimal price when blockchain technology is not applied. And, wholesale price and service price will decrease with the increase of blockchain technology application costs. Therefore, TPLSP should take the initiative to increase the sharing ratio to maximize the profits of each participant.

(3) In any decision-making mode, the decision-making and profits of each participant in the supply chain will increase with the improvement of consumer environmental protection awareness and freshness preference and decrease with the increase of carbon emission reduction cost and fresh-keeping cost. When consumers' environmental protection awareness and freshness preference are high, the unit retail price of fresh product is the highest under the decentralized decision-making when applying blockchain technology. In the centralized decision-making mode, the retailer will reduce retail price and expand market demand for the total profits of the supply chain, so the total profits of the system will be higher.

(4) Only through the contract coordination of "revenue sharing + double cost sharing" will the profit of the TPLSP reduce. When the parameters are controlled within a reasonable threshold range, the contract coordination mechanism of "two-part tariff + revenue sharing + double cost sharing" can ensure that the unit retail price, carbon emission reduction level, and fresh-keeping effort level are consistent with the optimal results of centralized decision-making and realize the Pareto improvement of the economic benefits of each participant in the supply chain.

6.2. Outlook. At present, this study still has some limitations. First of all, this paper only considers low carbon and blockchain technology as a background and does not delve into the specific measures of carbon emission reduction and the investment method of blockchain technology. Secondly, this paper only studies the supply chain of fresh agricultural products with a single offline channel and lacks market competition factors that consider online channels. Finally, this paper does not consider the government's regulatory mechanism for applying blockchain technology to the supply chain of fresh agricultural products and making decisions on carbon emission reduction and freshness-keeping [51]. Therefore, future research can explore specific measures to reduce carbon emissions in the supply chain of fresh agricultural products from the perspective of carbon cap and trade and can explore the dynamic investment decision of fresh agricultural product supply chain applying blockchain technology from the perspective of the multi-subject game [52] and also can combine online and offline channels from the perspective of government supervision, then comprehensively consider the market environment of fresh agricultural products, so as to provide more comprehensive solutions for the sustainable development of enterprises [53].

Appendix

Proof of Theorem 1. According to the converse solution method, first, find the partial derivative with respect to p^n of the retailer's profit function, order $\partial\pi_s^n/\partial p^n = 0$ can be obtained: $p^n = (\alpha + \lambda\gamma\theta + \lambda k\beta + \omega)/2$. Substitute it into equation (2) to get the supplier's profit function: $\pi_g^n = [(\omega - c - f)(\alpha - \omega + \lambda\gamma\theta + \lambda k\beta)]/2$. Then, taking the partial derivative of the supplier's profit function with respect to ω^n, order $\partial\pi_g^n/\partial\omega^n = 0$ can be obtained: $\omega^n = (\alpha + c + f + \lambda\gamma\theta + \lambda k\beta)/2$. Substituting p^n and ω^n into equation (3), the Hessian matrix of π_t^n with respect to f^n, θ^n, and β^n can be obtained:

$$H^n = \begin{bmatrix} \dfrac{\partial^2\pi_t^n}{\partial\theta^2} & \dfrac{\partial^2\pi_t^n}{\partial\theta\partial\beta} & \dfrac{\partial^2\pi_t^n}{\partial\theta\partial f} \\[2ex] \dfrac{\partial^2\pi_t^n}{\partial\beta\partial\theta} & \dfrac{\partial^2\pi_t^n}{\partial\beta^2} & \dfrac{\partial^2\pi_t^n}{\partial\beta\partial f} \\[2ex] \dfrac{\partial^2\pi_t^n}{\partial f\partial\theta} & \dfrac{\partial^2\pi_t^n}{\partial f\partial\beta} & \dfrac{\partial^2\pi_t^n}{\partial f^2} \end{bmatrix} = \begin{bmatrix} -h & 0 & \dfrac{\lambda\gamma}{4} \\[2ex] 0 & -b & \dfrac{\lambda k}{4} \\[2ex] \dfrac{\lambda\gamma}{4} & \dfrac{\lambda k}{4} & -\dfrac{1}{2} \end{bmatrix}. \tag{A.1}$$

It can be known from the Hessian matrix that when $\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 8hb < 0$, π_t^n has a unique optimal solution. Find the partial derivatives of π_t^n with respect to f^n, θ^n, and β^n and set them to 0 to obtain f^{n*}, θ^{n*}, and β^{n*}. Substituting equations f^{n*}, θ^{n*}, and β^{n*} into equations p^n and ω^n and can be obtained ω^{n*} and p^{n*}. The optimal profits of the retailer, the supplier, and the TPLSP can be obtained from the above-given formulas.

Proof of Theorem 2. Same as Theorem 1, according to the converse solution method, order $\partial\pi_s^o/\partial p^o = 0$ can be obtained p^o, order $\partial\pi_g^o/\partial\omega^o = 0$ can be obtained ω^o, and substitute it into equation (7), the Hessian matrix of π_t^o with respect to f^o, θ^o, and β^o can be obtained:

$$H^o = \begin{bmatrix} \dfrac{\partial^2 \pi_t^o}{\partial \theta^2} & \dfrac{\partial^2 \pi_t^o}{\partial \theta \partial \beta} & \dfrac{\partial^2 \pi_t^o}{\partial \theta \partial f} \\ \dfrac{\partial^2 \pi_t^o}{\partial \beta \partial \theta} & \dfrac{\partial^2 \pi_t^o}{\partial \beta^2} & \dfrac{\partial^2 \pi_t^o}{\partial \beta \partial f} \\ \dfrac{\partial^2 \pi_t^o}{\partial f \partial \theta} & \dfrac{\partial^2 \pi_t^o}{\partial f \partial \beta} & \dfrac{\partial^2 \pi_t^o}{\partial f^2} \end{bmatrix} = \begin{bmatrix} -h & 0 & \dfrac{\gamma}{4} \\ 0 & -b & \dfrac{k}{4} \\ \dfrac{\gamma}{4} & \dfrac{k}{4} & -\dfrac{1}{2} \end{bmatrix}. \tag{A.2}$$

It can be known from the Hessian matrix that when $hb > 0$ and $(hk^2 + b\gamma^2 - 8hb)/16 < 0$, π_t^o has a unique optimal solution. Find the partial derivatives of π_t^o with respect to f^o, θ^o, and β^o and set them to 0 to obtain f^{o*}, θ^{o*}, β^{o*}, ω^{o*}, and p^{o*}. The optimal profit of the retailer, the supplier, and the TPLSP can be obtained from the above-given formulas.

Proof of Lemma 1. From the previous assumptions and the results of the Hessian matrix, it can be known that $0 < \lambda^2 (hk^2 + b\gamma^2) - 8hb < hk^2 + b\gamma^2 - 8hb$, $(\alpha + 3c_2 - c - c_1) > (a - c)\lambda > 0$, and $hk^2 - hb + b\gamma^2 < 0$. Therefore, in any case, $\theta^{o*} - \theta^{n*} > 0$, $\beta^{o*} - \beta^{n*} > 0$, $p^{o*} \geq p^{n*}$, $\pi_s^{o*} - \pi_s^{n*} > 0$, $\pi_g^{o*} - \pi_g^{n*} > 0$, and $\pi_t^{o*} - \pi_t^{n*} > 0$.

When $c_1 [(1 - 2\delta)(hk^2 + b\gamma^2) + 4(4\delta - 1)hb] - c_2 (hk^2 + b\gamma^2 + 4hb) < 0$, $f^{o*} - f^{n*} > 0$; when $[c_1 (1 - \delta) + c - 2c_2 - c\lambda^2](hk^2 + b\gamma^2) - 2hb(c_1 - 4\delta c_1 + 2c + c_2) < 0$, $\omega^{o*} - \omega^{n*} > 0$; when $(c_1 - c\lambda^2)(hk^2 + b\gamma^2) + (c - 3c_2)(hk^2 + b\gamma^2 - \ hb) - hb(c + c_1) < 0$, $p^{o*} - p^{n*} > 0$. In summary, the conclusion of Lemma 1 can be drawn.

Proof of Theorem 3. First, the Hessian matrix of π^z can be obtained about θ^{z*}, β^{z*}, and p^{z*}:

$$H^z = \begin{bmatrix} \dfrac{\partial^2 \pi^z}{\partial \theta^2} & \dfrac{\partial^2 \pi^z}{\partial \theta \partial \beta} & \dfrac{\partial^2 \pi^z}{\partial \theta \partial p} \\ \dfrac{\partial^2 \pi^z}{\partial \beta \partial \theta} & \dfrac{\partial^2 \pi^z}{\partial \beta^2} & \dfrac{\partial^2 \pi^z}{\partial \beta \partial p} \\ \dfrac{\partial^2 \pi^z}{\partial p \partial \theta} & \dfrac{\partial^2 \pi^z}{\partial p \partial \beta} & \dfrac{\partial^2 \pi^z}{\partial p^2} \end{bmatrix} = \begin{bmatrix} -h & 0 & \gamma \\ 0 & -b & k \\ \gamma & k & -2 \end{bmatrix}. \tag{A.3}$$

It can be known from the Hessian matrix that there is a unique optimal solution for π^z when $hb > 0$, $\lambda^2 hk^2 + \lambda^2 b\gamma^2 - 2hb < 0$. Find the partial derivatives of θ^z, β^z, and p^z, with respect to π^z, and set them to 0 to obtain θ^{z*}, β^{z*}, p^{z*}, and π^{z*}.

Proof of Lemma 2. From the previous assumptions and the results of the Hessian matrix, it can be known that $0 < \lambda^2 (hk^2 + b\gamma^2) - 8hb < hk^2 + b\gamma^2 - 8hb$, $(\alpha + 3c_2 - c - c_1) > (a - c)\lambda > 0$, and $hk^2 - hb + b\gamma^2 < 0$. Therefore, in any case, $p^{z*} - p^{o*} < 0$, $\theta^{z*} - \theta^{o*} > 0$, $\beta^{z*} - \beta^{o*} > 0$, and $\pi^{z*} - \pi_s^{o*} - \pi_g^{o*} - \pi_t^{o*} > 0$. In summary, the conclusion of Lemma 2 can be drawn.

Proof of Lemma 3. From the previous assumptions and the results of the Hessian matrix, it can be known that $\alpha + 3c_2 - c - c_1 > 0$, $hk^2 + b\gamma^2 - 8hb < 0$, and $hk^2 + b\gamma^2 - 2hb < 0$. Therefore, it can be concluded that $\{\partial\theta^{o/z*}/\partial c$, $\partial\theta^{o/z*}/\partial c_1$, $\partial\theta^{o/z*}/\partial h$, $\partial\theta^{o/z*}/\partial b$, $\partial\beta^{o/z*}/\partial c$, $\partial\beta^{o/z*}/\partial c_1$, $\partial\beta^{o/z*}/\partial h$, $\partial\beta^{o/z*}/\partial b, \partial\pi_{s/g/t}^{o*}/\partial c, \partial\pi_{s/g/t}^{o*}/\partial c_1, \partial\pi_{s/g/t}^{o*}/\partial h, \partial\pi_{s/g/t}^{o*}/\partial b, \partial\pi^{z*}/\partial c$ $, \partial\pi^{z*}/\partial c_1, \partial\pi^{z*}/\partial h, \partial\pi^{z*}/\partial b, \partial p^{o/z*}/\partial h, \partial p^{o/z*}/\partial b, \partial p^{o/z*}/\partial c_2,$ $\partial f/\omega^{o*}/\partial h, \partial f/\omega^{o*}/\partial h, \partial f/\omega^{o*}/\partial b\}$ <0; $\{\partial\theta^{o/z*}/\partial c_2, \partial\theta^{o/z*}/\partial\gamma$, $\partial\theta^{o/z*}/\partial k$, $\partial\beta^{o/z*}/\partial c_2$, $\partial\beta^{o/z*}/\partial\gamma$, $\partial\beta^{o/z*}/\partial k$, $\partial\pi_{s/g/t}^{o*}/\partial c_2$, $\partial\pi_{s/g/t}^{o*}/\partial\gamma$, $\partial\pi_{s/g/t}^{o*}/\partial k$, $\partial\pi^{z*}/\partial c_2$, $\partial\pi^{z*}/\partial\gamma$, $\partial\pi^{z*}/\partial k$, $\partial p^{o/z*}/\partial\gamma$, $\partial p^{o/z*}/\partial k, \partial p^{o/z*}/\partial c, \partial p^{o/z*}/\partial c_1, \partial f/\omega^{o*}/\partial c_2, \partial f/\omega^{o*}/\partial\gamma$, and $\partial f/\omega^{o*}/\partial k\}$ >0. When $\delta > hk^2 + b\gamma^2 - 4hb/hk^2 + b\gamma^2 - 16hb$, $\partial f^{o*}/\partial c_1 > 0$. When $\delta > hk^2 + b\gamma^2 - 2hb/hk^2 + b\gamma^2 - 8hb$, $\partial\omega^{o*}/\partial c_1 < 0$. In summary, the conclusion of Lemma 3 can be drawn.

Proof of Theorem 4. According to the converse solution method, let the partial derivative of π_s^d with respect to p^d be 0 to obtain p^d, substitute it into equation (12) to obtain ω^d in the same way, and then substitute ω^d into p^d to obtain p^{d1}. If the contract can achieve effective coordination, the optimal unit retail price of fresh product, carbon emission reduction level, and fresh-keeping effort level under the contract coordination should be equal to the optimal result of centralized decision-making, therefore $p^{d*} = p^{z*}$, $\theta^{d*} = \theta^{z*}$, and $\beta^{d*} = \beta^{z*}$. Let $p^{d1} = p^{z*}$, it can be obtained f^{d*}. Substitute θ^{d*}, β^{d*}, and f^{d*} into ω^d to get ω^{d*}. Then, substituting the above formulas into formulas (11)–(13), the optimal profits of retailer, supplier, and TPLSP can be obtained.

Proof of Lemma 4. Adding formulas (16)–(18) can get $\pi_s^{d*} + \pi_g^{d*} + \pi_t^{d*} = \pi^{z*}$; from the previous assumptions and the results of the Hessian matrix, it can be known that $\alpha + 3c_2 - c - c_1 > 0$, $hk^2 + b\gamma^2 - 2hb < 0$, and $0 \leq \varphi, \eta \leq 1$. If the contract can achieve effective coordination, it should satisfy that the optimal profits of each subject under contract coordination are greater than the optimal profits of decentralized decision-making. Therefore, the thresholds for φ and η at $\pi_s^{d*} - \pi_s^{o*} > 0$ are $0 < \varphi \leq \varphi_1$, $0 < \eta \leq 1$, or $\varphi_1 < \varphi < \varphi_2$; the thresholds for φ and η at $\pi_g^{d*} - \pi_g^{o*} > 0$ are $0 < \varphi < 1$ and $0 < \eta < 1$; the thresholds for φ and η at $\pi_t^{d*} - \pi_t^{o*} > 0$ do not exist; that is, when $0 \leq \varphi, \eta \leq 1$, $\pi_t^{d*} > \pi_t^{o*}$ cannot be obtained.

Proof of Lemma 5. It can be obtained by calculation that when $\pi_s^{d*} - T_1 - \pi_s^{o*} > 0$, the thresholds of φ, η, T_1, and T_2 are $0 < \varphi \leq \varphi_1$, $0 < \eta \leq 1$, $0 < T_1 < T_{11}$ or $\varphi_1 < \varphi < \varphi_2$, $0 < \eta < \eta_1$, and $0 < T_1 < T_{11}$; when $\pi_g^{d*} - T_2 - \pi_g^{o*} > 0$, the thresholds for φ, η, T_1, and T_2 are $0 < \varphi < 1$, $0 < \eta < 1$, and $0 < T_2 < T_{21}$; when $\pi_t^{d*} + T_1 + T_2 - \pi_t^{o*} > 0$, the thresholds for φ, η, T_1, and T_2 are $0 < \varphi < 1$, $0 < \eta < 1$ and $0 < T_1 < T_{12}$, $T_2 > T_{22}$ or $T_1 > T_{12}$, and $T_2 > 0$. Combining all the conditions gives the result of Lemma 5 immediately.

Data Availability

No data were available for this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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