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Research on Optimal Greenness Decision and Coordination of Interests in Green Supply Chain of Livestock Products

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Abstract: Animal husbandry is an important industry related to the national economy and people's livelihood, and its coordinated development can continuously enhance the quality, efficiency, and competitiveness of the livestock industry, and better meet the people's diversified consumption demand for livestock and poultry products. In this paper, considering the government's green subsidy to the leading enterprises in the green supply chain of livestock products, the article uses the stackelberg game method to establish the decision-making models of the green supply chain of livestock products led by the co-operatives and the slaughtering and processing enterprises, respectively, and measures the optimal greenness of the livestock products. Different from the previous optimal decision-making and coordination of interests in the case of only considering economic benefits, this paper combines economic and ecological benefits to construct a coordination mechanism of interests in the green supply chain of livestock products in line with the concept of ecological priority and green development. The conclusions showed that: (1) Under the background of considering economic and ecological benefits, the influence of greenness sensitivity factor, freshness sensitivity factor, and government subsidy factor on the decision-making of green supply chain of livestock products is not affected by the operation mode and decision-making scenario, with the increase in the three factors, the greenness, freshness, and total benefits of the green supply chain of livestock products. (2) The greenness, freshness, and total benefits of green supply chain of livestock products are higher in the operation mode led by slaughtering and processing enterprises, which is more favorable to the development of green supply chain of livestock products from the perspective of supply chain development. (3) Compared with decentralized decision-making mode, both benefit-sharing and cost-sharing contracts increase the greenness and freshness of livestock products, significantly reduce the retail price of livestock products, which improves the benefits of the co-operatives, slaughtering and processing enterprises, 3PL (third-party logistics) service providers, and retailers as well as the entire green supply chain of livestock products. Based on the research findings, this article proposes relevant management insights to better promote the coordination of interests in the green supply chain of livestock products.

Keywords: green supply chain of livestock products; optimal greenness decision; coordination contract; operation mode; stackelberg game

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Citation: Zhang, J.; Wang, M. Research on Optimal Greenness Decision and Coordination of Interests in Green Supply Chain of Livestock Products. *Sustainability* **2024**, *16*, 6806. https://doi.org/10.3390/su16166806

Received: 15 June 2024
Revised: 6 August 2024
Accepted: 6 August 2024
Published: 8 August 2024

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1. Introduction

Animal husbandry is an important industry related to the national economy and people's livelihood. Meat, eggs, and milk are important varieties of the people's "food basket" [1]. The Ministry of Agriculture and Rural Affairs in China issued the "14th Five-Year" National Animal Husbandry and Veterinary Medicine Sector Development Plan in 2021, which puts forward that China will have made significant progress in the modernization of animal husbandry by 2025 [2]. Since the 20th National Congress of the Communist Party of China, China has proposed to build an important production base for agricultural and livestock products and build a high-quality pattern of development of the animal husbandry industry. The construction of a high-quality development pattern

of animal husbandry can not only consider the maximization of the economic benefits of animal husbandry but also needs to consider the economic benefits, ecological benefits and social benefits to achieve the coordination and integration of the development, which is the key to whether animal husbandry can achieve high-quality development and whether the modernization goals of pastoral areas can be achieved.

The livestock supply chain connects consumers' "food basket" at one end and herdsmen's "money bag" at the other, which is a "converter" for the coordinated development of animal husbandry. The green supply chain of livestock products is an important carrier to achieve high-quality development of animal husbandry [3], in which the interest is the fundamental link between the green supply chain of livestock products. The interest coordination mechanism is the institutional guarantee for the distribution of benefits and risk-bearing in the green supply chain of livestock products. The construction of a scientific and reasonable benefit coordination mechanism can help to achieve the coordinated development of economic, ecological, and social benefits of the green supply chain of livestock products, which can better achieve the high-quality development of the entire animal husbandry industry.

However, there are currently problems in the development of green supply chains for livestock products in China, such as unequal distribution of benefits, information asymmetry, uneven sharing of green costs, imperfect risk sharing mechanisms, and ineffective interest coordination mechanisms [4,5]. In addition, some market entities blindly pursue economic benefits while neglecting ecological and social benefits, resulting in low operational efficiency of the green supply chain for livestock products. Besides, consumers pay more and more attention to the greenness and freshness of livestock products. Therefore, based on the previous research, this paper focuses on key research questions as follows: (1) How to make decisions on the optimal greenness of the green supply chain of livestock products? (2) How to deeply explore the main factors affecting the greenness of livestock products and the degree of influence? (3) How to achieve the coordination of interests in the entire green supply chain of livestock products while ensuring both their greenness and freshness? These are important issues to be solved in this paper.

An important contribution of this paper is to construct a four-level green supply chain of livestock products consisting of co-operatives, slaughtering and processing enterprises, retailers, and 3PL service providers, and conduct an in-depth study on the optimal decision-making and coordination of interests in the green supply chain of livestock products under government subsidies to make the study more realistic and objective. In addition, the article combines the characteristics of livestock products, comprehensively considers the economic and ecological benefits of the green supply chain of livestock products, researches the optimal decision-making of the green supply chain of livestock products, and considers the impact of the optimal decision-making results on the social benefits of the green supply chain for livestock products. At the same time, the article designs coordination contracts to achieve the coordination of interests in the green supply chain.

The remainder of the paper is organized as follows: Section 2 briefly reviews the relevant literature. Section 3 introduces the game analysis of participating subjects in the green supply chain of livestock products. Section 4 discusses a contract for the coordination of interests in the green supply chain of livestock products under different operation modes. Section 5 presents the conclusions and management insights.

2. Review of Relevant Literature

At present, scholars at home and abroad have carried out continuous exploration around the green supply chain of agricultural and livestock products, mainly focusing on the optimal decision-making, operation mode, and coordination of interests in the green supply chain.

Research on optimal decision-making in green supply chains of agricultural and livestock products mainly focuses on two or three levels. Fang et al. analyzed the effects of freshness input level and shelf service level of fresh agricultural products on the optimal

decision-making and profitability of a two-level supply chain [6]. Li and Ouyang constructed a two-level agricultural products supply chain considering the effects of time and temperature on the optimal decision-making of the supply chain of fresh agricultural products and the demand [7]. Hua and Ding considered the effect of market stochastic demand on the optimal decision-making of the green supply chain for agricultural products [8]. Park and Hu found that the factor of consumer green preference and the freshness sensitivity factor have a positive incentive effect on the performance of the three-level fresh product supply chain [9]. As an important participant in the green supply chain of agricultural and livestock products, 3PL service providers have an advantage over suppliers and retailers in preserving freshness of fresh agricultural products [10], so it is valuable to study the coordination of interests in the green supply chain of agricultural and livestock products with the participation of logistics service providers. Lv et al. considered a three-level fresh product supply chain consisting of a supplier, a third-party logistics company, and two competing retailers, in which the supplier co-operates with the 3PL service providers on the cold chain and product traceability [11]. Feng and Gu focused on the coordination problem of the three-level fresh product supply chain, found that 3PL domination led to an increase in its own profit [12]. The importance of logistics service providers in the green supply chain of livestock products is undoubted, but the green supply chain of livestock products involved in the production activities of the livestock industry is very complex, including not only the whole process from the supply of forage, breeding, production and breeding, and slaughter and processing to the distribution of the sale of the whole process, but also includes animal welfare and government policy considerations. Therefore, a purely two- or three-level green supply chain of livestock products cannot meet the actual production needs, and a multi-level green supply chain of livestock products should be studied in the light of production needs.

Due to the perishable nature of agricultural and livestock products, which make the green supply chain of agricultural and livestock products distinctly different from other supply chains, the degree of greenness and freshness have become important factors affecting the decision-making of the green supply chain of agricultural and livestock products. For example, Chen et al. introduced the variable of greenness in their study to explore the game problem in the dual-channel agricultural supply chain and emphasized the important role of greenness in improving the efficiency of the agricultural supply chain [13]. Liu et al. introduced brand goodwill on this basis and explored the trajectory of product greenness and brand goodwill [14]. Chen et al. focused on the impact of the 3PL freshness level on each participating subject as well as the total profit of the agricultural products supply chain [15]. Yang and Lu took into account the impact of freshness level of fresh agricultural products on the purchasing power of the market [16]. To promote ecological protection, the government will implement green subsidy policies to further promote the development of green supply chains. Zhang et al. studied a three-level green supply chain composed of government, manufacturer, and retailer, and found that government green subsidies have a positive effect on the development of green supply chains [17]. The study by Zhou and Fu also showed that government subsidies help promote the development of the green supply chain [18].

With regard to the operation mode of the green supply chain of livestock products, existing studies have mainly analyzed the supply chain system for agricultural and livestock products and its coordination of interests from the perspective of "leading enterprises in the agricultural and animal husbandry industry" or "retailers". Few studies have been carried out from the perspective of "co-operatives", which represent the interests of herdsmen. For example, Song and Gao established a green supply chain game model under retailers and found that the retailer-led revenue-sharing contract has a higher level of greening [19]. Giri et al. analyzed the pricing and return decisions of the supply chain under centralized, decentralized manufacturer-led, retailer-led, and third-party-led scenarios and found that the retailer-led scenarios provided more profits [20]. Lin et al. incorporated the fairness preferences of upstream and downstream firms into a retailer-led supply chain decision-

making model to investigate the impact of the fairness preferences on the equilibrium decision-making and operational efficiency of the supply chain [21]. Gao and Mu used the modified Shapley value method to study the distribution of benefits of the main bodies in the alliance of a "co-operative-led agricultural supply chain" [22]. Tu et al. studied the benefit distribution mechanism of farmers' professional co-operatives based on the supply chain perspective [23]. In addition, the operation mode of the green supply chain of agricultural and livestock products led by logistics service providers is also relatively rare, which is mainly attributed to the limitations of logistics service providers in terms of scale, resources, and capacity, which makes it difficult for them to assume the heavy responsibility of leading the supply chain.

Supply chain coordination is one of the main directions of supply chain management research, and the establishment of coordination mechanisms is often the main means to solve the problem of incoherence among supply chain members. In order to enable the supply chain to operate efficiently and stably, the benefits among the partners should be reasonably distributed. Yan et al. studied the product freshness decision-making of manufacturers and retailers in the fresh product supply chain and designed a benefit-sharing interest contract [24]. Yang et al. studied the benefit coordination mechanism of a three-level fresh product supply chain under unexpected events [25]. Xiong et al. studied the freshness input decisions of the supply chain and explored the impact of supply chain allies' preferences on benefit coordination [26]. Some scholars have also designed the benefit coordination mechanism under demand uncertainty, such as Feng et al. constructed a three-level agricultural supply chain and designed the contract of wholesale price to achieve the coordination of the supply chain [27]. Zhou et al. designed a choice contract to achieve coordination of interests and information sharing in a two-level fresh product supply chain under demand uncertainty [28]. Ma et al. studied the coordination of interests in a three-level fresh product supply chain involving logistics service providers based on the information asymmetry scenario [29]. The intervention of 3PL is of great practical significance for improving the circulation efficiency of the fresh product supply chain, but it also increases the complexity of the supply chain contract. Ma et al. studied the coordination of interests in a three-level agricultural product supply chain consisting of farmers, 3PL service providers, and retailers, and established a dynamic game model under the decentralized and centralized decision-making modes [30]. Zhang investigated the involvement of a 3PL service provider in the interest coordination of the agricultural and livestock product supply chain and designed different contracts to achieve interest coordination [31].

The above literature has been studied from the single perspectives of a three-level green supply chain, greenness, freshness, and government subsidy, respectively, and there is a lack of studies that incorporate these factors into the green supply chain at the same time. Moreover, in the actual green supply chain operation of livestock products, the composition of the supply chain is more complex and rich in levels, usually involving multiple participating bodies. Among them, 3PL service providers, an important participant in the green supply chain of livestock products, are of great value to the study of coordination of interests in the green supply chain of livestock products. In addition, the existing literature focuses on economic benefits in the coordination of interests, and few studies consider the impact of ecological and social benefits on the optimal decision-making and coordination of interests in the green supply chain of livestock products.

Therefore, this study chooses a four-level green supply chain of livestock products, conducts an in-depth study on the optimal decision-making and coordination of interests in the green supply chain of livestock products, and considers the impact of the optimal decision-making results on the social benefits of the green supply chain of livestock products. The research results can further enrich the theoretical system of green supply chain optimal decision-making and benefit coordination.

3. Game Analysis of Participating Subjects in Green Supply Chain of Livestock Products

With the rapid development of the economy, and the upgrading of consumer attitudes, consumers' requirements for the quality of livestock products continue to improve, the consumer preference for green livestock products has increased significantly, and the greenness of livestock products has become an important influence on consumer purchasing choices.

In the process of the supply chain members' game, influenced by their own economic strength, information resources acquisition ability, brand influence, and other factors, each member of the supply chain may become the dominant player in the supply chain, such as Hongfa Group (National Trade Limited Liability Company in Siziwang county) and other large slaughtering and processing enterprises with strong strength, which usually occupy a dominant position in the supply chain. In addition, with the rapid development of co-operatives, a green supply chain of livestock products led by co-operatives has also been formed in recent years. In the game of the supply chain, the dominant has higher decision-making power.

Based on the aforementioned, this paper will investigate the optimal greenness, freshness and the total benefits of the green supply chain of livestock products under the two different operation modes.

3.1. Problem Description and Model Assumptions

3.1.1. Problem Description

The four-level green supply chain model of livestock products constructed in this paper is shown in Figure 1, in which the co-operatives are responsible for the breeding of livestock products and the provision of primary livestock products; the slaughtering and processing enterprises are responsible for the primary processing and deep processing of livestock products as well as the sales of livestock products to the retailers; the retailers are responsible for the retailing of livestock products to the consumers; and the 3PL service providers are responsible for the cold-chain logistics services of livestock products, so as to better ensure the freshness and quality of livestock products and meet the high-quality demand of end-consumers for livestock products.

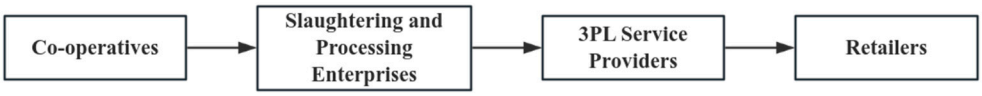


Figure 1. Green supply chain structure for livestock products.

Before the arrival of the sales season, the slaughtering and processing enterprises place orders of q in quantities according to the end-consumers' demand and the general requirement of greenness to the upstream co-operatives, which supply the products according to the order quantities of the slaughtering and processing enterprises, and then sell them to the slaughtering and processing enterprises at the wholesale price w per unit; the slaughtering and processing enterprises process the products according to the consumers' requirement of greenness g_r and sell them to the downstream retailers at the retail price p_m. At the same time, the 3PL service provider is commissioned to provide relevant cold chain logistics services at a price p_l. The 3PL service provider ensures the freshness f_r level of the products by providing high-quality cold chain logistics services; the retailers sell the livestock products to consumers at the retail price p. Consumers can measure their purchasing decision based on the retail price p, the greenness g_r, and the freshness f_r of the livestock products.

3.1.2. Model Assumptions and Notation

In order to make the model expression more intuitive and concise, the relevant parameters and symbols involved in the decision-making model are described as shown in Table 1 (the superscript S denotes the co-operative-led operation mode and M denotes the

slaughtering and processing enterprise-led operation mode; cd denotes the centralized decision-making scenario; dd denotes the decentralized decision-making scenario):

Table 1. Parameters and variables related to the game model of green supply chain of livestock products.

Notation	Clarification
p	Retail prices of livestock products
g_r	Level of greenness of livestock products
f_r	Level of freshness of livestock products
w	Wholesale prices of livestock products
p_m	Prices of intensively processed livestock products
p_l	Prices of services in logistics
Π_{Tr}	Total benefits of green supply chain of livestock products
Π_{En}	Economic benefits of green supply chain of livestock products
Π_{El}	Ecological benefits of green supply chain of livestock products
Π_s	Benefits of co-operatives
Π_m	Benefits of slaughtering and processing enterprises
Π_r	Benefits of retailers
Π_l	Benefits of 3PL service providers
c_s	Unit production costs of livestock products
c_m	Unit processing costs of livestock products
c_r	Unit cost of sales of livestock products
c_l	Unit logistics service costs for livestock products
D	Quantity demanded
a	Livestock products market size
α	Marginal cost coefficients for green inputs
β	Marginal cost factor for fresh inputs
λ	Retail price sensitivity factor
μ	Greenness sensitivity factor
η	Freshness sensitivity factor
s_0	Government subsidy factor for slaughtering and processing enterprises
s_m	Government subsidy factor for co-operatives

Assumption 1. *Each subject in the green supply chain of livestock products is completely rational and seeks to maximize its own interests; each member of the supply chain shares information and the information is completely symmetric; and they are all risk-neutral.*

Assumption 2. *The demand for livestock products is affected by a combination of factors such as freshness, greenness, retail price, etc. The demand function is as follows:* $D = a - \lambda p + \mu g_r + \eta f_r$.

Assumption 3. *The green investment cost and the greenness of livestock products is a quadratic function relationship [32]; the specific functional relationship formula is:* $C_1 = \alpha g_r^2/2$.

Assumption 4. *The cost of preservation investment and the level of freshness of livestock products is a quadratic function; the specific functional relationship is:* $C_2 = \beta f_r^2/2$.

Assumption 5. *The government needs to formulate relevant government subsidy policies in order to promote the development of the green supply chain of livestock products, to incentivize co-operatives and slaughtering and processing enterprises to make green innovation efforts and contributions, respectively, and to advocate and guide consumers toward green consumption. It is assumed that the government will subsidize different leading enterprises in the green supply chain of livestock products.*

Specific government subsidies are listed below:

Government subsidies to co-operatives: As there are more subsidies in the farming sector, including subsidies for livestock breed improvement, machinery and equipment, shed subsidies, and manure treatment subsidies, the government will subsidize the co-operative's green investment costs according to a certain subsidy factor of $s_0\alpha g_r^2/2$. For

example, the government of Chifeng City subsidizes the nature co-operative's machinery and equipment inputs.

Government subsidies to slaughtering and processing enterprises: Generally speaking, government subsidies to manufacturers are based on the level of green innovation efforts made by the manufacturer to produce the product. According to this definition, the amount of subsidy per unit of livestock product is $s_m g_r$, and the government subsidy increases as the level of greenness of the product increases.

Assumption 6. *Referring to the study of Cao Yu et al. [33], this paper also assumes that the total amount of government subsidies S is fixed and equal, which is* $S = s_0 \alpha g_r^2/2 = s_m g_r$.

Assumption 7. *This paper takes the total benefit of the whole green supply chain of livestock products as the decision-making goal, and the total benefit includes economic benefit and ecological benefit. Among them, the economic benefit under centralized decision-making is the total profit of the green supply chain of livestock products, and the economic benefit under decentralized decision-making is the sum of the profits of each participating subject; the ecological benefit under centralized and decentralized decision-making is the product of the greenness of the unit product and the market demand [34]; the total benefit of the green supply chain of livestock products* (Π_{Tr}) = *the economic benefit of the green supply chain of livestock products* (Π_{En}) + *the ecological benefit of the green supply chain of livestock products* (Π_{El}).

Assumption 8. *Referring to the study of scholars Cao Yu et al., social welfare (SW) consists of the economic benefits of the green supply chain of livestock products, ecological benefits of the green supply chain of livestock products, government subsidies, and consumer surplus [35].*

3.2. The Game Model of Green Supply Chain of Livestock Products Led by Co-Operatives

3.2.1. Centralized Decision-Making Led by Co-Operatives

The co-operatives occupy a dominant position in the green supply chain of livestock products, and the operation mode led by co-operatives is as shown in Figure 2.

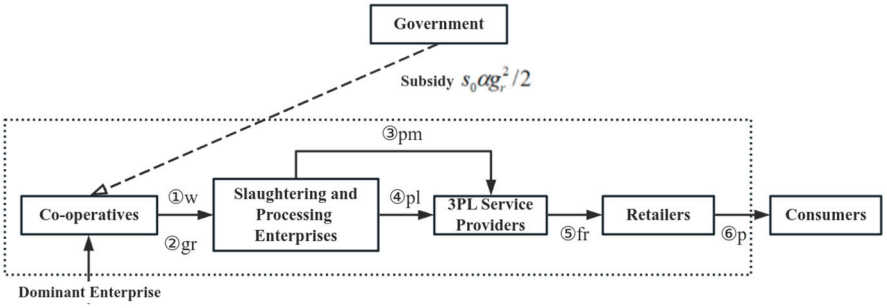


Figure 2. The operation mode of the green supply chain of livestock products led by co-operatives.

Co-operatives in this mode tend to be larger in scale. Co-operatives participating in this kind of green supply chain alliance of livestock products have a larger number of members, cover a larger area, have a higher degree of mechanical automation, and have a more advanced level of management. Large-scale operation is the key to the co-operatives' dominant position in the green supply chain alliance of livestock products. For example, the Talinhua Co-operatives of Arukolqin county, which has its own trademark and has obtained green food certification, established a co-operative relationship with local slaughtering and processing enterprises, occupying a dominant position in the supply chain.

Based on the above assumptions, the economic benefit function, ecological benefit function, total benefit function, and social welfare function of the green supply chain of livestock products under the centralized decision-making led by co-operatives are as follows:

Economic benefits of green supply chains of livestock products:

$$\Pi_{En}^{Scd} = (p - c_s - c_m - c_r - c_l)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}(1 - s_0)\alpha g_r^2 - \frac{1}{2}\beta f_r^2 \quad (1)$$

Ecological benefits of green supply chains of livestock products:

$$\Pi_{El}^{Scd} = (a - \lambda p + \mu g_r + \eta f_r) g_r \quad (2)$$

Total benefits of green supply chains of livestock products:

$$\Pi_{Tr}^{Scd} = (p - c_s - c_m - c_r - c_l + g_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}(1 - s_0)\alpha g_r^2 - \frac{1}{2}\beta f_r^2 \quad (3)$$

Social welfare:

$$\begin{aligned} SW^{Scd} = {} & (p - c_s - c_m - c_r - c_l + g_r)(a - \lambda p + \mu g_r + \eta f_r) \\ & -\tfrac{1}{2}(1 - s_0)\alpha g_r^2 - \tfrac{1}{2}\beta f_r^2 + \tfrac{1}{2}(a - \lambda p + \mu g_r + \eta f_r)^2 \end{aligned} \quad (4)$$

In the centralized decision-making scenario, the overall objective is to maximize the total benefits of the green supply chain of livestock products, and the decision variables are retail price p, greenness g_r, and freshness f_r of livestock products.

The Hessian matrix about these three decision variables is as follows:

$$H(p, g_r, f_r) = \begin{bmatrix} \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial p^2} & \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial p \partial g_r} & \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial p \partial f_r} \\ \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial g_r \partial p} & \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial {g_r}^2} & \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial g_r \partial f_r} \\ \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial f_r \partial p} & \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial f_r \partial g_r} & \frac{\partial^2 \Pi_{Tr}^{Scd}}{\partial f_r^2} \end{bmatrix} = \begin{bmatrix} -2\lambda & \mu - \lambda & \eta \\ \mu - \lambda & 2\mu + \alpha(s_0 - 1) & \eta \\ \eta & \eta & -\beta \end{bmatrix} \quad (5)$$

$$D_1^{Scd} = -(-2\lambda) = 2\lambda \quad (6)$$

$$D_2^{Scd} = \begin{vmatrix} -2\lambda & \mu - \lambda \\ \mu - \lambda & 2\mu + \alpha(s_0 - 1) \end{vmatrix} = 2\alpha\lambda - 2\lambda\mu - \lambda^2 - \mu^2 - 2\alpha\lambda s_0 \quad (7)$$

$$\begin{aligned} D_3^{Scd} &= -\begin{vmatrix} -2\lambda & \mu - \lambda & \eta \\ \mu - \lambda & 2\mu + \alpha(s_0 - 1) & \eta \\ \eta & \eta & -\beta \end{vmatrix} \\ &= -(\alpha\eta^2 + \beta\lambda^2 + \beta\mu^2 - 2\alpha\beta\lambda + 2\beta\lambda\mu - \alpha\eta^2 s_0 + 2\alpha\beta\lambda s_0) \end{aligned} \quad (8)$$

According to the Hessian matrix negative definite condition, the optimal decision exists when $2\lambda > 0$, $2\alpha\lambda - 2\lambda\mu - \lambda^2 - \mu^2 - 2\alpha\lambda s_0 > 0$, and $-(\alpha\eta^2 + \beta\lambda^2 + \beta\mu^2 - 2\alpha\beta\lambda + 2\beta\lambda\mu - \alpha\eta^2 s_0 + 2\alpha\beta\lambda s_0) > 0$.

Let $\frac{\partial \Pi_{Tr}^{Scd}}{\partial p} = 0$, $\frac{\partial \Pi_{Tr}^{Scd}}{\partial g_r} = 0$, $\frac{\partial \Pi_{Tr}^{Scd}}{\partial f_r} = 0$, then:

$$g_r^{Scd^*} = \frac{\beta(\lambda + \mu)(a - \lambda c_s - \lambda c_m - \lambda c_l - \lambda c_r)}{(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2} \quad (9)$$

$$f_r^{Scd^*} = \frac{\alpha\eta(a - \lambda c_s - \lambda c_m - \lambda c_l - \lambda c_r)(1 - s_0)}{(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2} \quad (10)$$

$$p^{Scd^*} = \frac{a + \eta f_r^{Scd^*} + (\mu - \lambda) g_r^{Scd^*} + \lambda(c_l + c_r + c_m + c_s)}{2\lambda} \quad (11)$$

Substituting the above optimal decisions into the benefit functions of the green supply chain of livestock products, the optimal economic benefit, the optimal ecological benefit,

the optimal total benefit, and the social welfare of the whole green supply chain of livestock products can be obtained as follows:

$$\begin{aligned}\Pi_{En}{}^{Scd^*} = (p^{Scd^*} - c_s - c_m - c_r - c_l)(a - \lambda p^{Scd^*} + \mu g_r^{Scd^*} + \eta f_r^{Scd^*}) \\ -\tfrac{1}{2}(1 - s_0)\alpha(g_r^{Scd^*})^2 - \tfrac{1}{2}\beta(f_r^{Scd^*})^2\end{aligned} \tag{12}$$

$$\Pi_{El}^{Scd^*} = (a - \lambda p^{Scd^*} + \mu g_r^{Scd^*} + \eta f_r^{Scd^*})g_r^{Scd^*} \tag{13}$$

$$\begin{aligned}\Pi_{Tr}{}^{Scd^*} = (p^{Scd^*} - c_s - c_m - c_r - c_l + g_r^{Scd^*})(a - \lambda p^{Scd^*} + \mu g_r^{Scd^*} + \eta f_r^{Scd^*}) \\ -\tfrac{1}{2}(1 - s_0)\alpha(g_r^{Scd^*})^2 - \tfrac{1}{2}\beta(f_r^{Scd^*})^2\end{aligned} \tag{14}$$

$$\begin{aligned}SW^{Scd^*} = (p^{Scd^*} - c_s - c_m - c_r - c_l + g_r^{Scd^*})(a - \lambda p^{Scd^*} + \mu g_r^{Scd^*} + \eta f_r^{Scd^*}) \\ -\tfrac{1}{2}(1 - s_0)\alpha(g_r^{Scd^*})^2 - \tfrac{1}{2}\beta(f_r^{Scd^*})^2 + \tfrac{1}{2}(a - \lambda p^{Scd^*} + \mu g_r^{Scd^*} + \eta f_r^{Scd^*})^2\end{aligned} \tag{15}$$

3.2.2. Decentralized Decision-Making Led by Co-Operatives

In the decentralized decision-making scenario, each participant in the green supply chain of livestock products does not co-operate with each other. The co-operative firstly decides the wholesale price of livestock products w and the greenness level g_r; secondly, the slaughtering and processing enterprise decides the price of livestock products p_m; then the 3PL service provider decides the price of logistics services p_l and freshness level f_r. Finally, the retailer decides the retail price p. At the same time, the government subsidizes the co-operative's green investment costs. Based on Stackelberg game theory, the optimal decision-making of the green supply chain of livestock products under the decentralized decision-making scenario is obtained by using the backward induction method.

$$\Pi_s^{Sdd} = (w - c_s + g_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}(1 - s_0)\alpha g_r^2 \tag{16}$$

$$\Pi_m^{Sdd} = (p_m - w - c_m)(a - \lambda p + \mu g_r + \eta f_r) \tag{17}$$

$$\Pi_r^{Sdd} = (p - p_m - p_l - c_r)(a - \lambda p + \mu g_r + \eta f_r) \tag{18}$$

$$\Pi_l^{Sdd} = (p_l - c_l)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}\beta f_r^2 \tag{19}$$

Firstly, the Hessian matrix of the retailer's benefit function Π_r^{Sdd} with respect to p is as follows:

$$H(p) = \left[\frac{\partial^2 \Pi_r^{Sdd}}{\partial p^2}\right] = -2\lambda \tag{20}$$

When $-2\lambda < 0$, there exists a unique optimal solution.

$$p^{Sdd^*} = \frac{(a + \mu g_r + \eta f_r) + \lambda(p_m + p_l + c_r)}{2\lambda} \tag{21}$$

$$D_1^{Sdd} = \frac{(a + \mu g_r + \eta f_r) - \lambda(p_m + p_l + c_r)}{2} \tag{22}$$

Substitute (22) into (19):

$$\Pi_l^{Sdd} = (p_l - c_l)\frac{(a + \mu g_r + \eta f_r) - \lambda(p_m + p_l + c_r)}{2} - \frac{1}{2}\beta {f_r}^2 \tag{23}$$

$$H(p_l, f_r) = \begin{bmatrix} \frac{\partial^2 \Pi_l^{Sdd}}{\partial p_l^2} & \frac{\partial^2 \Pi_l^{Sdd}}{\partial p_l \partial f_r} \\ \frac{\partial^2 \Pi_l^{Sdd}}{\partial f_r \partial p_l} & \frac{\partial^2 \Pi_l^{Sdd}}{\partial f_r^2} \end{bmatrix} = \begin{bmatrix} -\lambda & \frac{\eta}{2} \\ \frac{\eta}{2} & -\beta \end{bmatrix} \tag{24}$$

When $4\lambda\beta - \eta^2 > 0$, a unique optimal solution exists.

$$p_l^{Sdd^*} = \frac{2\beta(a + \mu g_r) - 2\lambda\beta(p_m + c_r + c_l) + (4\lambda\beta - \eta^2)c_l}{4\lambda\beta - \eta^2} \tag{25}$$

$$fr^{Sdd^*} = \frac{\eta(a + \mu g_r) - \lambda\eta(p_m + c_r + c_l)}{4\lambda\beta - \eta^2} \tag{26}$$

$$D_2^{Sdd} = \frac{\lambda\beta(a + \mu g_r - \lambda p_m - \lambda c_r - \lambda c_l)}{4\lambda\beta - \eta^2} \tag{27}$$

Substitute (27) into (17):

$$\Pi_m^{Sdd} = (p_m - w - c_m)\frac{\lambda\beta(a + \mu g_r - \lambda p_m - \lambda c_r - \lambda c_l)}{4\lambda\beta - \eta^2} \tag{28}$$

$$H(p_m) = \left[\frac{\partial^2 \Pi_m^{Sdd}}{\partial {p_m}^2}\right] = -\frac{2\lambda^2\beta}{4\lambda\beta - \eta^2} \tag{29}$$

When $-2\lambda^2\beta < 0$, there exists a unique solution.

$$p_m^{Sdd^*} = \frac{(a + \mu g_r) + \lambda(w + c_m - c_r - c_l)}{2\lambda} \tag{30}$$

$$D_3^{Sdd} = \frac{\lambda\beta(a + \mu g_r - \lambda w - \lambda c_m - \lambda c_r - \lambda c_l)}{8\lambda\beta - 2\eta^2} \tag{31}$$

Substitute (31) into (16):

$$\Pi_s^{Sdd} = (w - c_s + g_r)\frac{\lambda\beta(a + \mu g_r - \lambda w - \lambda c_m - \lambda c_r - \lambda c_l)}{8\lambda\beta - 2\eta^2} - \frac{1}{2}(1 - s_0)\alpha {g_r}^2 \tag{32}$$

$$H(w, g_r) = \begin{bmatrix} \frac{\partial^2 \Pi_s^{Sdd}}{\partial w^2} & \frac{\partial^2 \Pi_s^{Sdd}}{\partial w \partial g_r} \\ \frac{\partial^2 \Pi_s^{Sdd}}{\partial g_r \partial w} & \frac{\partial^2 \Pi_s^{Sdd}}{\partial {g_r}^2} \end{bmatrix} = \begin{bmatrix} -\frac{\beta\lambda^2}{4\lambda\beta - \eta^2} & -\frac{\beta\lambda(\lambda - \mu)}{2(4\lambda\beta - \eta^2)} \\ -\frac{\beta\lambda(\lambda - \mu)}{2(4\lambda\beta - \eta^2)} & \alpha(s_0 - 1) + \frac{\beta\lambda\mu}{4\lambda\beta - \eta^2} \end{bmatrix} \tag{33}$$

When $-(\beta^2\lambda^4 - 16\alpha\beta^2\lambda^3 + 2\beta^2\lambda^3\mu + \beta^2\lambda^2\mu^2 + 4\alpha\beta\eta^2\lambda^2 + 16\alpha\beta^2\lambda^3 s_0 - 4\alpha\beta\eta^2\lambda^2 s_0) > 0$, there exists a unique solution.

$$w^{Sdd^*} = \frac{A_{11}(a + \lambda c_s - \lambda c_m - \lambda c_l - \lambda c_r) + A_{12}(\lambda c_m + \lambda c_l + \lambda c_r - a) - \beta\lambda\mu(\lambda + \mu)c_s}{\lambda[(16\alpha\beta\lambda - 4\alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2]} \tag{34}$$

$$A_{11} = (8\alpha\lambda\beta - 2\alpha\eta^2)(1 - s_0) \tag{35}$$

$$A_{12} = \beta\lambda(\lambda + \mu) \tag{36}$$

$$g_r^{Sdd^*} = \frac{\beta(\lambda + \mu)(a - \lambda c_l - \lambda c_m - \lambda c_r - \lambda c_s)}{(16\alpha\beta\lambda - 4\alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2} \tag{37}$$

Substituting the above optimal solutions into their respective benefit functions, the optimal benefits of each participant under the decentralized decision-making model can be obtained as follows:

$$\begin{aligned} \Pi_s^{Sdd^*} = (w^{Sdd^*} - c_s + g_r^{Sdd^*})(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) \\ -(1 - s_0)\alpha(g_r^{Sdd^*})^2/2 \end{aligned} \tag{38}$$

$$\Pi_m^{Sdd^*} = (p_m^{Sdd^*} - w^{Sdd^*} - c_m)(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) \tag{39}$$

$$\Pi_r^{Sdd^*} = (p^{Sdd^*} - p_m^{Sdd^*} - p_l^{Sdd^*} - c_r)(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) \tag{40}$$

$$\Pi_l^{Sdd^*} = (p_l^{Sdd^*} - c_l)(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) - \beta (f_r^{Sdd^*})^2/2 \tag{41}$$

Economic benefits of green supply chains of livestock products:

$$\begin{aligned}\Pi_{En}^{Sdd^*} = (p^{Sdd^*} - c_s - c_m - c_r - c_l)(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) \\ -(1 - s_0)(g_r^{Sdd^*})^2/2 - (f_r^{Sdd^*})^2/2\end{aligned} \tag{42}$$

Ecological benefits of green supply chains of livestock products:

$$\Pi_{El}^{Sdd^*} = (a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) g_r^{Sdd^*} \tag{43}$$

Total benefits of green supply chains of livestock products:

$$\begin{aligned}\Pi_{Tr}^{Sdd^*} = (p^{Sdd^*} - c_s - c_m - c_r - c_l + g_r^{Sdd^*})(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) \\ -(1 - s_0)\alpha (g_r^{Sdd^*})^2/2 - \beta (f_r^{Sdd^*})^2/2\end{aligned} \tag{44}$$

Social welfare of green supply chains of livestock products:

$$\begin{aligned}SW^{Sdd^*} = (p^{Sdd^*} - c_s - c_m - c_r - c_l + g_r^{Sdd^*})(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*}) \\ -\tfrac{1}{2}(1 - s_0)\alpha (g_r^{Sdd^*})^2 - \tfrac{1}{2}\beta (f_r^{Sdd^*})^2 + \tfrac{1}{2}(a - \lambda p^{Sdd^*} + \mu g_r^{Sdd^*} + \eta f_r^{Sdd^*})^2\end{aligned} \tag{45}$$

3.2.3. Parametric Analysis Led by Co-Operatives

Proposition 1.

$\frac{\partial g_r^{Scd^*}}{\partial \mu} > 0$, $\frac{\partial f_r^{Scd^*}}{\partial \mu} > 0$, $\frac{\partial p^{Scd^*}}{\partial \mu} > 0$, $\frac{\partial \Pi_{Tr}^{Scd^*}}{\partial \mu} > 0$; $\frac{\partial g_r^{Scd^*}}{\partial \eta} > 0$, $\frac{\partial f_r^{Scd^*}}{\partial \eta} > 0$, $\frac{\partial p^{Scd^*}}{\partial \eta} > 0$, $\frac{\partial \Pi_{Tr}^{Scd^*}}{\partial \eta} > 0$;
$\frac{\partial g_r^{Scd^*}}{\partial s_0} > 0$, $\frac{\partial f_r^{Scd^*}}{\partial s_0} > 0$, $\frac{\partial p^{Scd^*}}{\partial s_0} > 0$, $\frac{\partial \Pi_{Tr}^{Scd^*}}{\partial s_0} > 0$

Proposition 1 suggests that in the operation mode led by co-operatives, the greenness sensitivity factor, freshness sensitivity factor, and government subsidy factor are positively correlated with the retail price, the greenness, the freshness, and the total benefits of the green supply chain of livestock products in the centralized decision-making scenario.

Certificate:

$$\frac{\partial g_r^{Scd^*}}{\partial \mu} = \frac{\beta(a - \lambda C)[(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) + \beta(\lambda + \mu)^2]}{[(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2]^2}$$

By the negative determinant of the Hessian matrix $H(p, g_r, f_r)$, it follows that $(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2 > 0$, $(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) + \beta(\lambda + \mu)^2 > 0$. And $g_r^{Scd^*} > 0$, $\beta(\lambda + \mu)(a - \lambda C) > 0$. Therefore, it is proved that $\frac{\partial g_r^{Scd^*}}{\partial \mu} > 0$. The rest of the proofs of the positivity and negativity of the required partial derivatives are similar to this one, and will not be proved one by one here, and Proposition 1 is proved.

Proposition 2.

$\frac{\partial g_r^{Sdd^*}}{\partial \mu} > 0$, $\frac{\partial f_r^{Sdd^*}}{\partial \mu} > 0$, $\frac{\partial p^{Sdd^*}}{\partial \mu} > 0$, $\frac{\partial \Pi_{Tr}^{Sdd^*}}{\partial \mu} > 0$; $\frac{\partial g_r^{Sdd^*}}{\partial \eta} > 0$, $\frac{\partial f_r^{Sdd^*}}{\partial \eta} > 0$, $\frac{\partial p^{Sdd^*}}{\partial \eta} > 0$, $\frac{\partial \Pi_{Tr}^{Sdd^*}}{\partial \eta} > 0$;
$\frac{\partial g_r^{Sdd^*}}{\partial s_0} > 0$, $\frac{\partial f_r^{Sdd^*}}{\partial s_0} > 0$, $\frac{\partial p^{Sdd^*}}{\partial s_0} > 0$, $\frac{\partial \Pi_{Tr}^{Sdd^*}}{\partial s_0} > 0$

Proposition 2 suggests that in the operation mode led by co-operatives under decentralized decision-making, the greenness sensitivity factor, freshness sensitivity factor, and government subsidy factor are positively correlated with the retail price, the greenness, the freshness, and the total benefits of the green supply chain of livestock products.

Certificate:

$$\frac{\partial f_r^{Scd^*}}{\partial \eta} = \frac{[\alpha(a-\lambda C)(1-s_0)-(\lambda+\mu)\gamma^2][(2\alpha\beta\lambda-\alpha\eta^2)(1-s_0)-\beta(\lambda+\mu)^2]}{[(2\alpha\beta\lambda-\alpha\eta^2)(1-s_0)-\beta(\lambda+\mu)^2]^2} + \frac{2\alpha\eta(1-s_0)[\alpha\eta(a-\lambda C)(1-s_0)-\eta(\lambda+\mu)\gamma^2]}{[(2\alpha\beta\lambda-\alpha\eta^2)(1-s_0)-\beta(\lambda+\mu)^2]^2}$$

By the negative determinant of the Hessian matrix $H(p, g_r, f_r)$, $(2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2 > 0$, and $f_r^{Scd^*} > 0$, so $\alpha\eta(a - \lambda C)(1 - s_0) - \eta(\lambda + \mu)\gamma^2 > 0$. Then $\frac{\partial g_r^{Scd^*}}{\partial \mu} > 0$. The rest of the proofs of the positivity and negativity of the required partial derivatives are similar to this one, and Proposition 2 is proved.

Propositions 1 and 2 show that as consumers tend to buy livestock products with higher greenness and freshness, the main participants in the green supply chain of livestock products will inevitably increase greenness and freshness inputs to meet consumer demand, such as adopting more ecological and environmentally friendly breeding methods and using more advanced freshness preservation technologies, thus improving the greenness and freshness of livestock products; accordingly, the production cost of the enterprise will also rise. In order to protect their own benefits, enterprises will adopt the strategy of moderately increasing the retail price of livestock products. As consumers are willing to pay higher market prices, the market demand for livestock products will be continuously improved, and the benefits of the supply chain participants will also be increased.

3.3. Game Model of Green Supply Chain of Livestock Products Led by Slaughtering and Processing Enterprises

3.3.1. Centralized Decision-Making Led by Slaughtering and Processing Enterprises

The slaughtering and processing enterprise is another important link that affects the quality of livestock products in addition to breeding. As a key point linking upstream production and downstream circulation, the role of slaughtering and processing enterprises is crucial, and as a leading enterprise in the green supply chain of livestock products, the slaughtering technology and efficiency of the enterprise determine the level of greenness of livestock products.

The slaughtering and processing enterprises are usually large and strong, and as the leading enterprises in the green supply chain of livestock products, they usually have their own brands, such as Chifeng Hongfa Group's "Cilechuan" and "Xuewai Rising Sun", which have established a good image and reputation in the channel and have obtained green food certification from the China Green Food Development Centre. The operation mode led by slaughtering and processing enterprises is shown in Figure 3.

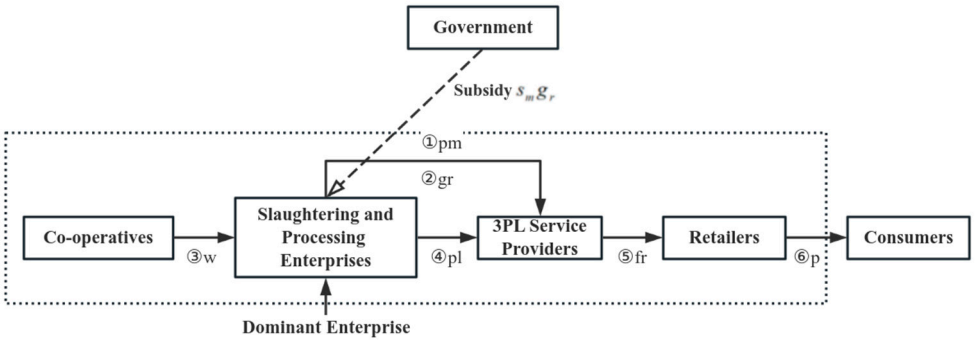


Figure 3. Green supply chain operation mode of livestock products led by slaughtering and processing enterprises.

Based on the above assumptions, the economic benefits of the green supply chain of livestock products can be obtained:

$$\Pi_{\mathrm{En}}^{Mcd} = (p - c_s - c_m - c_r - c_l + s_m g_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}\alpha g_r^2 - \frac{1}{2}\beta f_r^2 \quad (46)$$

The ecological benefits of the green supply chain of livestock products:

$$\Pi_{El}^{Mcd} = (a - \lambda p + \mu g_r + \eta f_r) g_r \quad (47)$$

The total benefits of the green supply chain of livestock products:

$$\Pi_{Tr}^{Mcd} = (p - c_s - c_m - c_r - c_l + s_m g_r + g_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}\alpha g_r^2 - \frac{1}{2}\beta f_r^2 \quad (48)$$

The social welfare of the green supply chain of livestock products:

$$\begin{aligned} SW^{Mcd} = {} & (p - c_s - c_m - c_r - c_l + s_m g_r + g_r)(a - \lambda p + \mu g_r + \eta f_r) \\ & -\tfrac{1}{2}\alpha g_r^2 - \tfrac{1}{2}\beta f_r^2 + \tfrac{1}{2}(a - \lambda p + \mu g_r + \eta f_r)^2 \end{aligned} \quad (49)$$

In the centralized decision-making scenario, the overall objective is to maximize the total benefits of the green supply chain of livestock products, and the decision variables are retail price of livestock products p, greenness g_r, and freshness f_r of livestock products.

According to the Hessian matrix negative definite condition, the optimal decision exists when $2\lambda > 0$, $-\lambda^2 s_m^2 - 2\lambda^2 s_m - \lambda^2 - 2\lambda\mu s_m - 2\lambda\mu + 2\lambda\alpha - \mu^2 > 0$ and $-(\alpha\eta^2 + \beta\lambda^2 s_m^2 + 2\beta\lambda^2 s_m + \beta\lambda^2 + 2\beta\lambda\mu s_m + 2\beta\lambda\mu - 2\alpha\beta\lambda + \beta\mu^2) > 0$.

$$g_r^{Mcd^*} = \frac{\beta(\lambda + \mu + \lambda s_m)(a - \lambda c_s - \lambda c_m - \lambda c_l - \lambda c_r)}{(2\alpha\beta\lambda - \alpha\eta^2) - \beta(\lambda + \mu)^2 - \beta\lambda^2 s_m^2 - 2\beta\lambda s_m(\lambda + \mu)} \quad (50)$$

$$f_r^{Mcd^*} = \frac{\alpha\eta(a - \lambda c_s - \lambda c_m - \lambda c_l - \lambda c_r)}{(2\alpha\beta\lambda - \alpha\eta^2) - \beta(\lambda + \mu)^2 - \beta\lambda^2 s_m^2 - 2\beta\lambda s_m(\lambda + \mu)} \quad (51)$$

$$p^{Mcd^*} = \frac{a + \eta f_r^{Mcd^*} + (\mu - \lambda - \lambda s_m) g_r^{Mcd^*} + \lambda(c_l + c_r + c_m + c_s)}{2\lambda} \quad (52)$$

Substituting the above optimal decision into the benefit functions of the green supply chain of livestock products, the optimal economic benefit, the optimal ecological benefit, and the optimal total benefit of the green supply chain of livestock products can be obtained as follows:

$$\begin{aligned} \Pi_{En}^{Mcd^*} = {} & (p^{Mcd^*} - c_l - c_r - c_m - c_s + s_m g_r^{Mcd^*})(a - \lambda p^{Mcd^*} + \mu g_r^{Mcd^*} + \eta f_r^{Mcd^*}) \\ & -\tfrac{1}{2}\alpha(g_r^{Mcd^*})^2 - \tfrac{1}{2}\beta(f_r^{Mcd^*})^2 \end{aligned} \quad (53)$$

$$\Pi_{El}^{Mcd^*} = (a - \lambda p^{Mcd^*} + \mu g_r^{Mcd^*} + \eta f_r^{Mcd^*}) g_r^{Mcd^*} \quad (54)$$

$$\begin{aligned} \Pi_{Tr}^{Mcd^*} = {} & (p^{Mcd^*} - c_l - c_r - c_m - c_s + s_m g_r^{Mcd^*} + g_r^{Mcd^*})(a - \lambda p^{Mcd^*} + \mu g_r^{Mcd^*} + \eta f_r^{Mcd^*}) \\ & -\tfrac{1}{2}\alpha(g_r^{Mcd^*})^2 - \tfrac{1}{2}\beta(f_r^{Mcd^*})^2 \end{aligned} \quad (55)$$

$$\begin{aligned} SW^{Mcd^*} = {} & (p^{Mcd^*} - c_l - c_r - c_m - c_s + s_m g_r^{Mcd^*} + g_r^{Mcd^*})(a - \lambda p^{Mcd^*} + \mu g_r^{Mcd^*} + \eta f_r^{Mcd^*}) \\ & -\tfrac{1}{2}\alpha(g_r^{Mcd^*})^2 - \tfrac{1}{2}\beta(f_r^{Mcd^*})^2 + \tfrac{1}{2}(a - \lambda p^{Mcd^*} + \mu g_r^{Mcd^*} + \eta f_r^{Mcd^*})^2 \end{aligned} \quad (56)$$

3.3.2. Decentralized Decision-Making Led by Slaughtering and Processing Enterprises

In the decentralized decision-making scenario, each participant in the supply chain makes decisions independently, and each participant takes the maximization of its own interests as its decision-making goal. As the leader of the supply chain, the slaughtering and processing enterprise firstly decides the price p_m and the greenness level g_r, the cooperative then decides the wholesale price w of livestock products, and the 3PL service

provider decides the price p_l and the freshness level f_r. Finally, the retailer decides the retail price p. Meanwhile, the government subsidizes the green investment cost of the slaughtering and processing enterprise. The benefit functions of each participant in the supply chain are as follows:

$$\Pi_s^{Mdd} = (w - c_s)(a - \lambda p + \mu g_r + \eta f_r) \tag{57}$$

$$\Pi_m^{Mdd} = (p_m - w - c_m + s_m g_r + g_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}\alpha g_r^2 \tag{58}$$

$$\Pi_r^{Mdd} = (p - p_m - p_l - c_r)(a - \lambda p + \mu g_r + \eta f_r) \tag{59}$$

$$\Pi_l^{Mdd} = (p_l - c_l)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}\beta f_r^2 \tag{60}$$

The optimal decision-making of the green supply chain of livestock products under the decentralized decision-making scenario is obtained by using the backward induction method as follows:

$$p^{Mdd^*} = \frac{(a + \mu gr + \eta fr) + \lambda(p_m + p_l + c_r)}{2\lambda} \tag{61}$$

$$p_l^{Mdd^*} = \frac{2\beta(a + \mu g_r) - 2\beta(\lambda p_m + \lambda c_r + \lambda c_l) + (4\lambda\beta - \eta^2)c_l}{4\lambda\beta - \eta^2} \tag{62}$$

$$f_r^{Mdd^*} = \frac{\eta(a + \mu g_r - \lambda p_m - \lambda c_r - \lambda c_l)}{4\lambda\beta - \eta^2} \tag{63}$$

$$w^{Mdd^*} = \frac{(a + \mu g_r) - \lambda(x + c_r + c_l - c_s)}{2\lambda} \tag{64}$$

$$g_r^{Mdd^*} = \frac{\beta(\lambda + \mu + \lambda s_m)(a - \lambda c_m - \lambda c_s - \lambda c_r - \lambda c_l)}{(16\alpha\lambda\beta - 4\alpha\eta^2) - \beta(\lambda + \mu)^2 - \beta\lambda^2 s_m^2 - 2\beta\lambda s_m(\lambda + \mu)} \tag{65}$$

$$p_m^{Mdd^*} = \frac{A_{21}(\lambda c_l + \lambda c_r - a) + A_{22}(2c_m + c_s - e)}{\lambda[8\alpha(\eta^2 - 4\lambda\beta) + \beta(2\lambda + \mu)^2 + 4\lambda\beta s_m(\lambda s_m + 2\lambda + \mu s_m)]} \tag{66}$$

$$A_{21} = -[6\alpha\eta^2 - 24\alpha\beta\lambda + 4\beta(\lambda + \lambda s_m)^2 + 2\lambda\beta\mu(1 + s_m)] \tag{67}$$

$$A_{22} = -(8\alpha\beta\lambda^2 - 2\alpha\lambda\eta^2 - \beta\lambda\mu^2 - 2\beta\lambda^2\mu - 2\beta\lambda^2\mu s_m) \tag{68}$$

Substituting the above optimal solutions into their respective benefit functions, the optimal benefits of each participant under the decentralized decision-making model can be obtained as follows:

$$\Pi_s^{Mdd^*} = (w^{Mdd^*} - c_s)(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) \tag{69}$$

$$\begin{aligned}\Pi_m^{Mdd^*} = {} & (p_m^{Mdd^*} - w^{Mdd^*} - c_m + s_m g_r^{Mdd^*})(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) \\ & -\tfrac{1}{2}\alpha(g_r^{Mdd^*})^2 + g_r^{Mdd^*}(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*})\end{aligned} \tag{70}$$

$$\Pi_r^{Mdd^*} = (p^{Mdd^*} - p_m^{Mdd^*} - p_l^{Mdd^*} - c_r)(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) \tag{71}$$

$$\Pi_l^{Mdd^*} = (p_l^{Mdd^*} - c_l)(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) - \frac{1}{2}\beta(f_r^{Mdd^*})^2 \tag{72}$$

$$\begin{aligned}\Pi_{En}^{Mdd^*} = {} & (p^{Mdd^*} - c_l - c_r - c_m - c_s + s_m g_r^{Mdd^*})(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) \\ & -\tfrac{1}{2}\alpha(g_r^{Mdd^*})^2 - \tfrac{1}{2}\beta(f_r^{Mdd^*})^2\end{aligned} \tag{73}$$

$$\Pi_{El}^{Mdd^*} = (a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) g_r^{Mdd^*} \tag{74}$$

$$\begin{aligned}\Pi_{TR}^{Mdd^*} = {} & (p^{Mdd^*} - c_l - c_r - c_m - c_s + s_m g_r^{Mdd^*} + g_r^{Mdd^*})(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) \\ & -\tfrac{1}{2}\alpha(g_r^{Mdd^*})^2 - \tfrac{1}{2}\beta(f_r^{Mdd^*})^2\end{aligned} \tag{75}$$

$$SW^{Mdd^*} = (p^{Mdd^*} - c_l - c_r - c_m - c_s + s_m g_r^{Mdd^*} + g_r^{Mdd^*})(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*}) - \frac{1}{2}\alpha(g_r^{Mdd^*})^2 - \frac{1}{2}\beta(f_r^{Mdd^*})^2 + \frac{1}{2}(a - \lambda p^{Mdd^*} + \mu g_r^{Mdd^*} + \eta f_r^{Mdd^*})^2 \quad (76)$$

3.3.3. Parametric Analysis Led by Slaughtering and Processing Enterprises

Proposition 3.

$$\frac{\partial g_r^{Mcd^*}}{\partial \mu} > 0, \frac{\partial f_r^{Mcd^*}}{\partial \mu} > 0, \frac{\partial p^{Mcd^*}}{\partial \mu} > 0, \frac{\partial \Pi_{Tr}^{Mcd^*}}{\partial \mu} > 0; \frac{\partial g_r^{Mcd^*}}{\partial \eta} > 0, \frac{\partial f_r^{Mcd^*}}{\partial \eta} > 0, \frac{\partial p^{Mcd^*}}{\partial \eta} > 0, \frac{\partial \Pi_{Tr}^{Mcd^*}}{\partial \eta} > 0;$$
$$\frac{\partial g_r^{Mcd^*}}{\partial s_m} > 0, \frac{\partial f_r^{Mcd^*}}{\partial s_m} > 0, \frac{\partial p^{Mcd^*}}{\partial s_m} > 0, \frac{\partial \Pi_{Tr}^{Mcd^*}}{\partial s_m} > 0$$

Proposition 3 shows that in the operation mode led by slaughtering and processing enterprises, the greenness sensitivity factor, the freshness sensitivity factor, and the government subsidy factor are positively correlated with the retail price, the greenness, the freshness, and the total benefits of the green supply chain of livestock products in the centralized decision-making scenario.

The proof process is the same as Proposition 1.

Proposition 4.

$$\frac{\partial g_r^{Mdd^*}}{\partial \mu} > 0, \frac{\partial f_r^{Mdd^*}}{\partial \mu} > 0, \frac{\partial p^{Mdd^*}}{\partial \mu} > 0, \frac{\partial \Pi_{Tr}^{Mdd^*}}{\partial \mu} > 0; \frac{\partial g_r^{Mdd^*}}{\partial \eta} > 0, \frac{\partial f_r^{Mdd^*}}{\partial \eta} > 0, \frac{\partial p^{Mdd^*}}{\partial \eta} > 0, \frac{\partial \Pi_{Tr}^{Mdd^*}}{\partial \eta} > 0;$$
$$\frac{\partial g_r^{Mdd^*}}{\partial s_m} > 0, \frac{\partial f_r^{Mdd^*}}{\partial s_m} > 0, \frac{\partial p^{Mdd^*}}{\partial s_m} > 0, \frac{\partial \Pi_{Tr}^{Mdd^*}}{\partial s_m} > 0$$

Proposition 4 shows that in the operation mode led by slaughtering and processing enterprises, under the decentralized decision-making scenario, the greenness sensitivity factor, the freshness sensitivity factor, and the government subsidy factor are positively correlated with the retail price, the greenness, the freshness, and the total benefits of the green supply chain of livestock products.

The proof process is the same as Proposition 2.

3.4. Comparative Analysis of Decision-Making Scenarios under Different Operation Modes

In this section, comparative analysis will be used to analyze the relationship between the decision variables in different decision-making scenarios under the two operation modes.

Proposition 5. *When* $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda + \mu) > (2\alpha\beta\lambda - \alpha\eta^2)s_0$, *it can get* $g_r^{Mcd^*} > g_r^{Scd^*}$; *When* $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda + \mu) > (16\alpha\beta\lambda - 4\alpha\eta^2)s_0$, *so* $g_r^{Mdd^*} > g_r^{Sdd^*}$.

From Proposition 5, it can be seen that the greenness of livestock products is higher in the slaughtering and processing enterprise-led mode of operation, both in the centralized and decentralized decision-making scenarios.

Certificate: The greenness of livestock products in the co-operative-led operation mode and the slaughtering and processing enterprise-led operation mode in the centralized decision-making scenario are as follows:

$$g_r^{Scd^*} = \frac{\beta(\lambda+\mu)(a-\lambda C)}{D_3^{Scd}}$$
$$g_r^{Mcd^*} = \frac{\beta(\lambda+\mu+\lambda s_m)(a-\lambda C)}{D_3^{Mcd}}$$
$$D_3^{Scd} = (2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) - \beta(\lambda + \mu)^2$$
$$D_3^{Mcd} = (2\alpha\beta\lambda - \alpha\eta^2) - \beta(\lambda + \mu)^2 - \beta\lambda^2 s_m^2 - 2\beta\lambda s_m(\lambda + \mu)$$
$$C = c_s + c_m + c_r + c_l$$

When $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda+\mu) > (16\alpha\beta\lambda - 4\alpha\eta^2)s_0$, it can get $D^{Sdd} > D^{Mdd}$, set an intermediate value g_r^2, $g_r^2 = \frac{\beta(\lambda+\mu+\lambda s_m)(a-\lambda C)}{D^{Sdd}}$, and there exists $g_r^{Mdd^*} > g_r^2$. $g_r^2 - g_r^{Sdd^*} = \frac{\beta\lambda s_m(a-\lambda C)}{D^{Sdd}}$, where $\beta > 0$, $\lambda > 0$, $s_m > 0$, $D^{Sdd} > 0$, $a - \lambda C > 0$, proves $g_r^{Mdd^*} > g_r^{Sdd^*}$.

Proposition 5 states that the greenness of livestock products under centralized and decentralized decision-making is affected by the combination of the greenness sensitivity factor, the freshness sensitivity factor, and the government subsidy factor. When consumer greenness sensitivity factor, freshness sensitivity factor, and government subsidy factor for slaughtering and processing enterprises are larger, while subsidy factor for co-operatives is smaller, the greenness of livestock products under the domination of slaughtering and processing enterprises is higher than that of livestock products under the domination of co-operatives.

The reason for the aforementioned is that when the slaughtering and processing enterprises are in the leading position in the green supply chain of livestock products, they can integrate upstream and downstream resources and control the whole process from production and breeding, slaughtering and processing to distribution and sales, etc. This integration ability makes it easier for the enterprises to promote the production of green livestock products and to ensure the greenness of the whole process of livestock products from the place of origin to the dining table. Moreover, the slaughtering and processing enterprises have strong technical innovation ability and can introduce and apply advanced production technology, equipment, and management mode to improve the production efficiency and quality of livestock products and further promote the greenness of livestock products.

Proposition 6. *When* $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda+\mu) > (2\alpha\beta\lambda - \alpha\eta^2)s_0$, *it can get* $f_r^{Mcd^*} > f_r^{Scd^*}$. *When* $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda+\mu) > (16\alpha\beta\lambda - 4\alpha\eta^2)s_0$, *it can get* $f_r^{Mdd^*} > f_r^{Sdd^*}$.

From Proposition 6, it is clear that the freshness of livestock products is higher in the slaughtering and processing enterprise-led mode of operation in both centralized and decentralized decision-making scenarios.

Certificate: The freshness of livestock products of the co-operative-led operation mode in the centralized decision-making scenario and the freshness of livestock products of the slaughtering and processing enterprise-led operation mode are as follows:

$$f_r^{Scd^*} = \frac{\alpha\eta(a-\lambda C)(1-s_0)}{D_3^{Scd}} \tag{77}$$

$$f_r^{Mcd^*} = \frac{\alpha\eta(a-\lambda C)}{D_3^{Mcd}} \tag{78}$$

When $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda+\mu) > (2\alpha\beta\lambda - \alpha\eta^2)s_0$ yields $D_3^{Scd} > D_3^{Mcd}$, set an intermediate value f_r^1, $f_r^1 = \frac{\alpha\eta(1-s_0)(a-\lambda C)}{D_3^{Mcd}}$, and there exists $f_r^1 > f_r^{Scd^*}$. $f_r^{Mcd^*} - f_r^1 = \frac{\alpha\eta s_0(a-\lambda C)}{D_3^{Mcd}}$, where $\alpha > 0$, $\lambda > 0$, $s_0 > 0$, $D_3^{Mcd} > 0$, $a - \lambda C > 0$, proves $f_r^{Mcd^*} > f_r^{Scd^*}$.

The freshness of livestock products in the decentralized decision-making scenario for the co-operative-led operation mode and the slaughter–processor-led operation mode are as follows:

$$f_r^{Sdd^*} = \frac{\alpha\eta(1-s_0)(a-\lambda C)}{D^{Sdd}} \tag{79}$$

$$f_r^{Mdd^*} = \frac{\alpha\eta(a-\lambda C)}{D^{Mdd}} \tag{80}$$

When $\beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda+\mu) > (16\alpha\beta\lambda - 4\alpha\eta^2)s_0$, it can get $D^{Sdd} > D^{Mdd}$. Setting an intermediate value f_r^2, $f_r^2 = \frac{\alpha\eta(a-\lambda C)}{D^{Sdd}}$, $f_r^2 < f_r^{Mdd^*}$. $f_r^2 - f_r^{Sdd^*} = \frac{\alpha\eta s_0(a-\lambda C)}{D^{Sdd}}$, where $\alpha > 0, \eta > 0, s_0 > 0$, $D^{Sdd} > 0$, when $a - \lambda c_s - \lambda c_m - \lambda c_r - \lambda c_l > 0$, it can get $f_r^2 - f_r^{Sdd^*} > 0$, which proves $f_r^{Mdd^*} > f_r^{Sdd^*}$.

Proposition 6 states that the freshness of livestock products under centralized and decentralized decision-making is affected by the combination of the greenness sensitivity factor, freshness sensitivity factor and government subsidy factor. When the greenness sensitivity factor, the freshness sensitivity factor and the government subsidy factor to slaughtering and processing enterprises are larger and the subsidy factor to co-operatives is smaller, the freshness of livestock products under the domination of slaughtering and processing enterprises is higher than that under the domination of co-operatives.

Proposition 7. *When* $\eta^2 - 2\beta\lambda > 0$, *it can get* $g_r^{Scd^*} > g_r^{Sdd^*}$ $g_r^{Mcd^*} > g_r^{Mdd^*}$.

From Proposition 7, it can be seen that the greenness of livestock products is better in centralized decision-making than decentralized decision-making in both of the two operation modes.

Certificate:

$D_3^{Sdd^*} - D_3^{Scd^*} = (16\alpha\beta\lambda - 4\alpha\eta^2)(1 - s_0) - (2\alpha\beta\lambda - \alpha\eta^2)(1 - s_0) > 3(4\alpha\beta\lambda - \alpha\eta^2)$, and there exists $4\beta\lambda - \eta^2 > 0$, so $D_3^{Sdd^*} > D_3^{Scd^*}$. $g_r^3 = \frac{(\eta^2 - 2\beta\lambda)\gamma^2 + \beta(\lambda+\mu)(a-\lambda C)}{D_3^{Sdd}}$, $g_r^3 < g_r^{Scd}$. Let $g_r^3 - g_r^{Sdd} = \frac{(\eta^2 - 2\beta\lambda)\gamma^2}{D_3^{Sdd}}$, when $\eta^2 - 2\beta\lambda > 0$, proves $g_r^{Scd} > g_r^{Sdd}$. The proof of $g_r^{Mcd} > g_r^{Mdd}$ is as above.

3.5. Numerical Analysis

3.5.1. Analysis of Game Results

The expressions of optimal decision-making under different decision-making scenarios and the optimal benefit functions of each participant are too complex to directly reflect the relationship between optimal decision-making and optimal benefit under different decision-making modes through analytical formulas. In reference to the common practice in most of the literature, this part will be analyzed in detail through the numerical simulation method. Under the preconditions of satisfying the basic assumptions of the model and the actual operating background of the green supply chain of livestock products, the values of relevant parameters are assigned as shown in the following Table 2.

Table 2. Assignment of values to the parameters in the model.

Parameters	a	λ	μ	η	c_s	c_m	c_r	c_l	α	β
Numerical Value	100	1.75	0.6	1.85	1.5	1.5	1	1.5	1	1

The optimal decisions and optimal benefits for different decision scenarios under the two operation modes are calculated and shown in Table 3.

Table 3 shows that regardless of the operation mode, centralized decision-making is more conducive to the efficient development of the whole green supply chain of livestock products, and the total benefits of the whole green supply chain of livestock products in the case of decentralized decision-making have limited room for growth, so it is necessary to design a reasonable coordination contract of interests to improve the level of greenness, freshness, and benefits of the various participants.

Under the centralized decision-making scenario, the greenness, freshness, retail price, total benefits, and social welfare of the green supply chain of livestock products are higher in the operation mode led by slaughtering and processing enterprises than in the operation mode led by the co-operatives.

Table 3. Optimal decision-making and optimal benefits of different decision-making modes under two operation modes.

	Operation Mode Led by Co-Operatives		Operation Mode Led by Slaughtering and Processing Enterprises	
	Centralized Decision-Making	Decentralized Decision-Making	Centralized Decision-Making	Decentralized Decision-Making
g_r	12.68	11.88	12.99	11.89
f_r	16.44	2.36	19.65	2.41
p	23.70	58.53	27.91	57.76
p_l	-	10.95	-	10.15
p_m	-	41.85	-	40.78
w	-	22	-	20.1
Π_s	-	213.69	-	157.08
Π_m	-	150	-	217.99
Π_r	-	23	-	40.71
Π_l	-	75.48	-	78.54
Π_{En}	107.17	331.89	232.97	377.17
Π_{El}	835.59	131.49	893.45	117.16
Π_{Tr}	942.76	463.38	1126.42	494.33
SW	5602.76	504.38	5667.74	549.59

In the decentralized decision-making scenario, the greenness, freshness, benefits of slaughtering and processing enterprises, benefits of 3PL service providers, benefits of retailers, total benefits of the green supply chain of livestock products, and the social welfare of livestock products in the slaughtering and processing enterprise-led operation mode are also higher than those in the co-operative-led operation mode. The retail price, wholesale price, and price of processed livestock products under the mode of operation led by slaughtering and processing enterprises are all lower than those under the co-operative-led mode. This indicates that the operation mode led by slaughtering and processing enterprises is more conducive to the long-term development of the whole green supply chain of livestock products, which further verifies the correctness and validity of the model's calculation results, and can provide theoretical guidance for the decision-making of relevant enterprises.

3.5.2. Analysis of the Impact of Relevant Parameters on Optimal Decision-Making in Green Supply Chains of Livestock Products

According to Propositions 1–4, substitute the values of relevant parameters in Table 2, and use Matlab software R2022a to draw the relationship between the greenness, freshness and total benefits of the livestock supply chain and the greenness sensitivity factor, freshness sensitivity factor, and the government's green subsidy factor for the dominant enterprise, as shown in Figures 4–7.

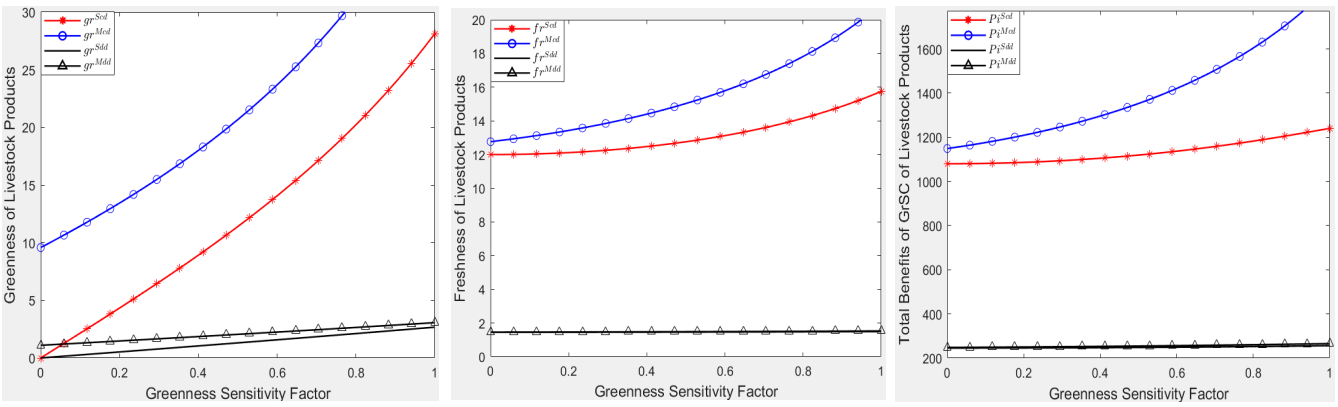


Figure 4. Relationship between g_r, f_r, Π_{Tr} and μ.

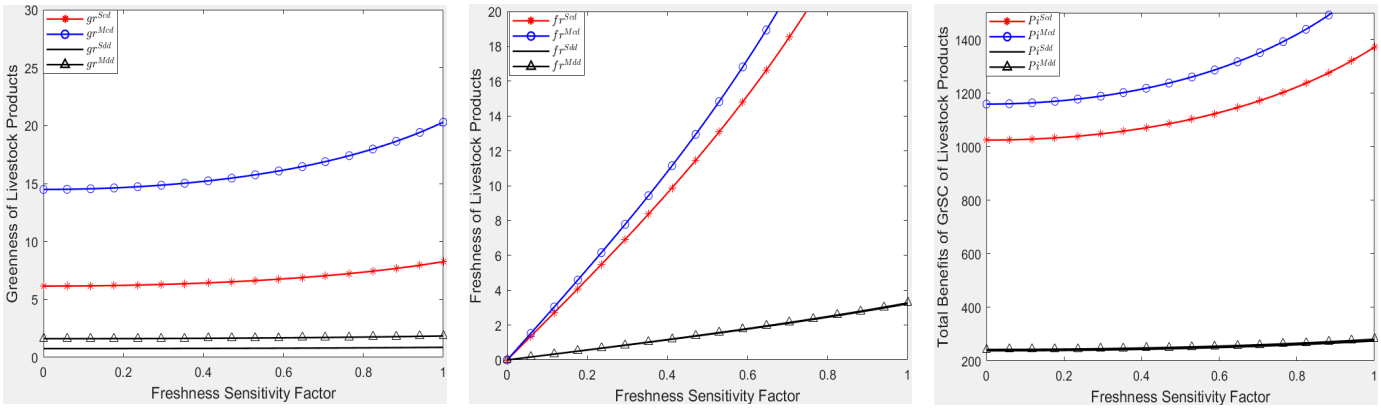


Figure 5. Relationship between g_r, f_r, Π_{Tr} and η.

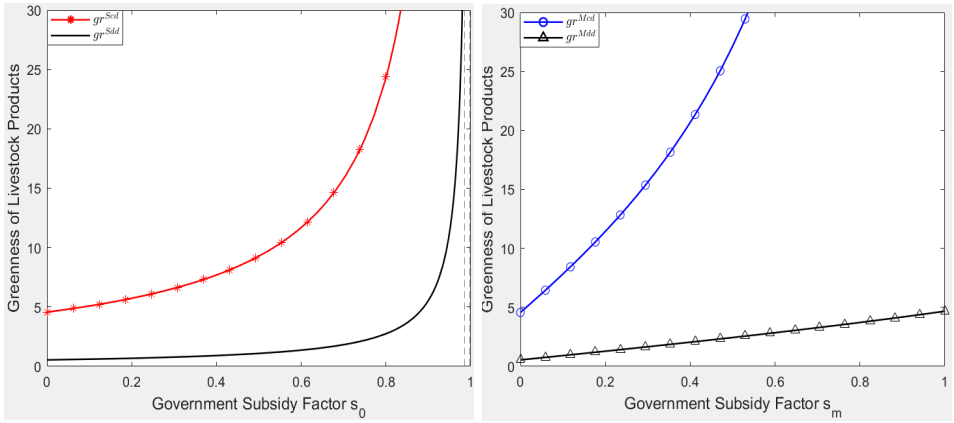


Figure 6. Relationship between g_r and government subsidy factor under different operation modes.

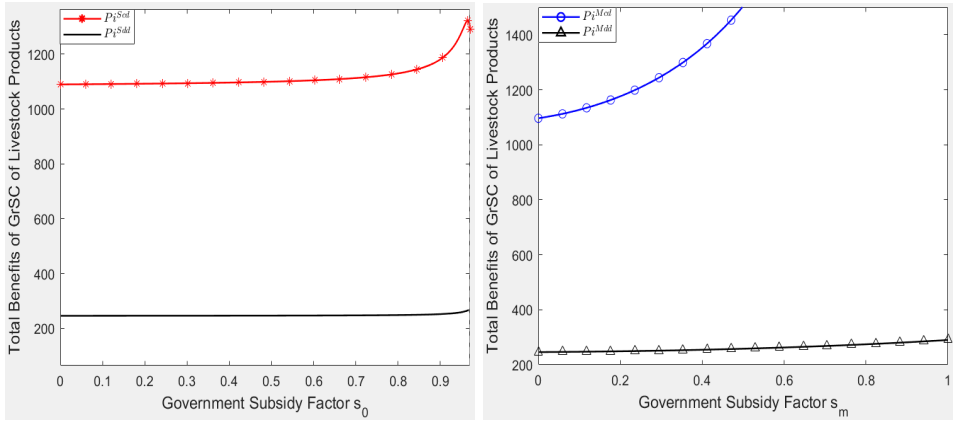


Figure 7. Relationship between Π_{Tr} and government subsidy factor under different operation modes.

From Figures 4 and 5, it can be seen that no matter which subject occupies a dominant position in the green supply chain of livestock products and which decision-making scenario is taken, the greenness, freshness, and the total benefits of the green supply chain of livestock products are all proportional to the greenness sensitivity factor and the freshness sensitivity factor, which further verifies Propositions 1–4.

This suggests that (1) the direction of the influence of the greenness and freshness sensitivity factor on the decision-making is not affected by the operation mode and decision-making scenario. (2) As the greenness and freshness sensitivity factor increase, the greenness and freshness of livestock products also increase.

The reasons for the aforementioned are as follows: With the enhancement of environmental awareness, consumers are more inclined to choose livestock products with a high level of greenness and freshness, which reflects the expectation of environmentally friendly consumers for the sustainable development of livestock products, and enterprises also hope that the green concepts of their products can resonate with consumers to a certain extent. The stronger the environmental protection mentality of consumers, the more incentives for supply chain members to carry out green R&D (research and development) enthusiasm.

(3) As the greenness and freshness sensitivity factor increase, the increase in the total green supply chain benefits of livestock products under the two decision-making scenarios becomes larger and larger.

The reasons for the aforementioned are as follows: As the greenness and freshness sensitivity factor increase, the greenness, freshness, and retail price of livestock products will increase accordingly, so consumers will be more inclined to buy livestock products with high greenness and freshness, and this preference will lead to the increase in market demand, which will attract more producers to join the green supply chain and realize a positive cycle and improve the total efficiency.

As can be seen from Figures 6 and 7, no matter which subject occupies the dominant position in the green supply chain of livestock products and which decision-making scenario is adopted, the greenness and the total benefits of the green supply chain of livestock products are directly proportional to the government's green subsidy factor to the dominant enterprise, which verifies the correctness of Propositions 1–4.

The reasons for the aforementioned are as follows: As the government green subsidy factor to the dominant enterprise increases, the greenness of livestock products in different decision-making scenarios in the two operation modes grows more and more, and the total benefit of the green supply chain of livestock products also grows. This shows that if the government provides green subsidies to the leading enterprises, it will stimulate the leading enterprises to carry out green research and development, which can improve the quality of livestock products, promote the development of green consumption, and help to improve the income level of herdsmen.

3.5.3. Comparative Analysis of Optimal Decision-Making and Optimal Benefits under Different Operation Modes

In this section, comparative analysis will be applied to compare the optimal decision-making and optimal benefits of the two operation modes under the centralized and decentralized decision-making scenarios, respectively.

As shown in Figure 8, the greenness, freshness of livestock products, and total benefits of the livestock supply chain in the centralized decision-making scenario are higher in the operation mode led by slaughtering and processing enterprises than in the operation mode led by co-operatives, which further validates Proposition 5.

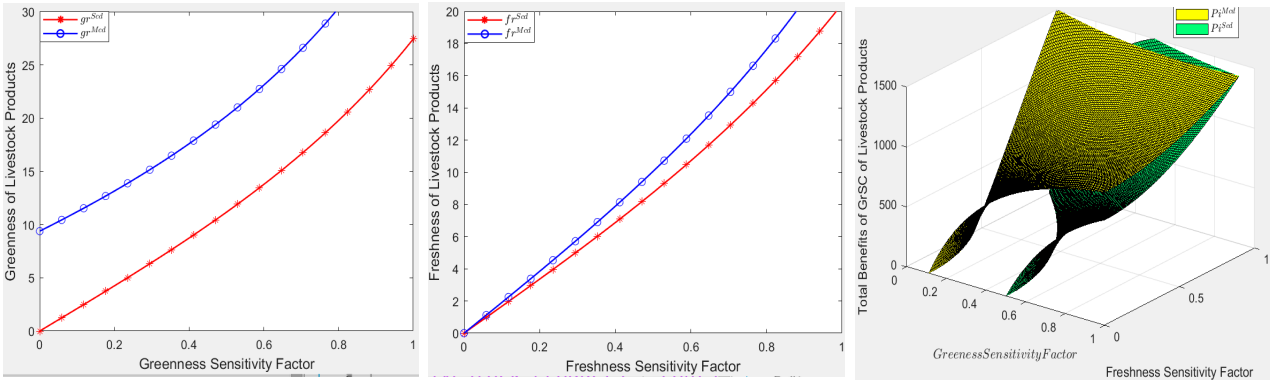


Figure 8. Comparison of optimal decision-making and optimal benefits of two operation modes under centralized decision-making.

From Figures 9 and 10, it can be seen that in the decentralized decision-making scenario, the greenness, freshness of livestock products, benefits of slaughtering and processing enterprises, and total benefits of the green supply chain of livestock products in the operation mode led by slaughtering and processing enterprises are higher than those in the operation mode led by co-operatives. This indicates that the operation mode led by slaughtering and processing enterprises has more advantages than the operation mode led by co-operatives in both the centralized and decentralized decision-making scenario.

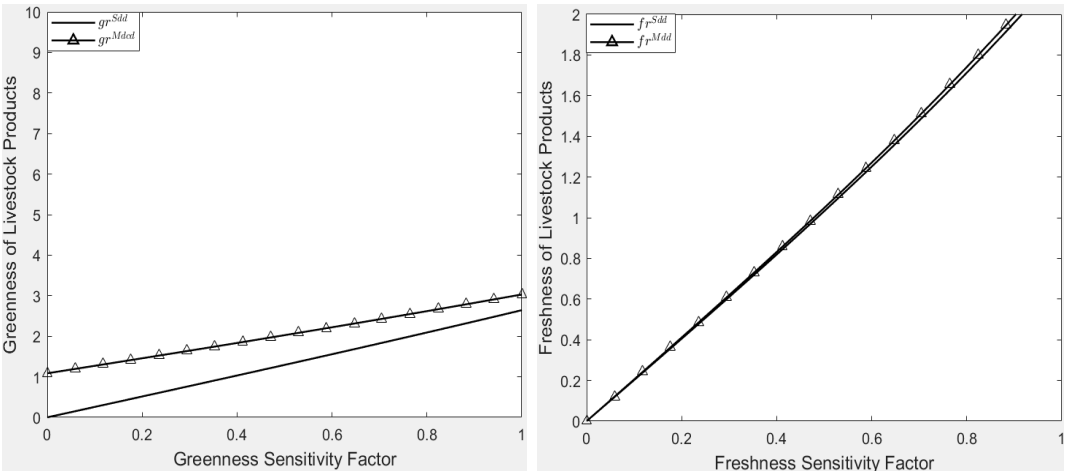


Figure 9. Comparison of the optimal greenness, freshness of two operation modes under decentralized decision-making.

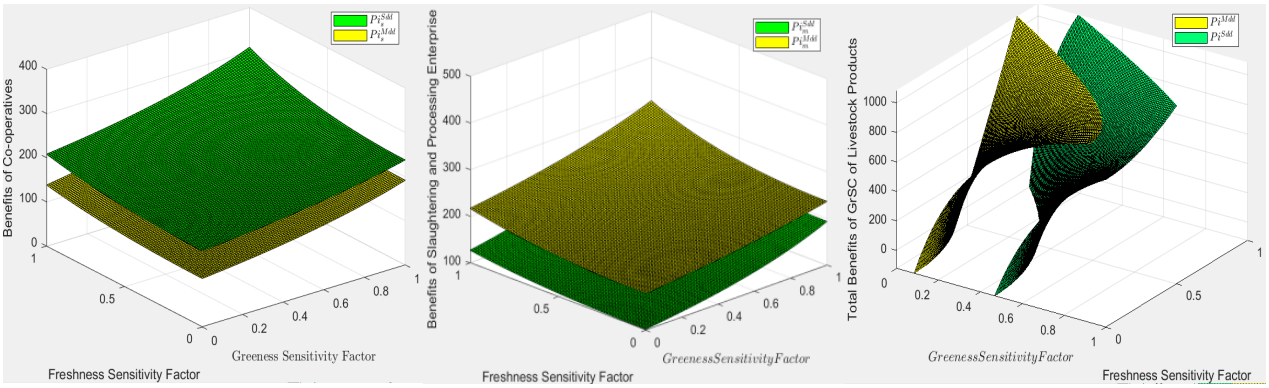


Figure 10. Comparison of the optimal benefits of two operation modes under decentralized decision-making.

The reasons are: (1) Slaughtering and processing enterprises usually have strong technological strength and can apply advanced production and processing technologies to improve the production environment and efficiency. These technologies include waste treatment, energy saving, and emission reduction, etc., which can help reduce environmental pollution, resource wastage, and enhance the sustainability of the green supply chain. (2) Slaughtering and processing enterprises usually possess more professional management capabilities and are able to formulate and implement strict operating procedures and standards. Such standardized and professional management can prompt enterprises to better control the environment and quality in the production and processing process, which is conducive to achieving the goal of a green supply chain. (3) As the core link in the green supply chain of livestock products, slaughtering and processing enterprises are responsible for collecting and recording information on various aspects of livestock product production, processing, and transport. Under the mode of centralized decision-making, slaughtering and processing enterprises can better share information with other supply

chain participants such as upstream co-operatives, downstream 3PL service providers, retailers, etc., so as to improve the transparency and traceability of the green supply chain. (4) Slaughtering and processing enterprises can better co-operate with other linked subjects. For example, they can co-operate with co-operatives to implement strict animal welfare standards and co-operate with 3PL service providers to improve the efficiency of cold chain logistics, etc., so as to strengthen the connection and coordination between various links in the supply chain, and promote the transformation of the whole supply chain to greening. (5) Slaughtering and processing enterprises bear the responsibility of providing green and high-quality livestock products to the market and can win the trust of consumers by providing high-quality green livestock products, which will in turn enhance the brand effect and competitiveness of enterprises.

In summary, the operation mode led by slaughtering and processing enterprises is more suitable for the development of the green supply chain of livestock products. This operation mode can achieve standardized management, information sharing, technical support, supply chain co-operation, and brand effect, thus promoting the green development of the livestock supply chain, realizing the improvement of the greenness and freshness of livestock products, and thus enhancing the total benefits of the green supply chain of livestock products.

4. Design Contract for Coordination of Interests in Green Supply Chains of Livestock Products under Different Operation Modes

In the two different operation modes, the optimal decision value under centralized decision-making is always better than the value under decentralized decision-making. This part will design the interest coordination contract, so that the total benefits of the whole green supply chain of livestock products and the benefits of each participant can be improved by Pareto.

4.1. Co-Operative-Led Benefit Coordination Contract Design for Green Supply Chain of Livestock Products

4.1.1. Cost-Sharing Contract

One way to reduce the investment costs of the co-operative and the 3PL service provider is to introduce a cost-sharing benefit coordination contract where the retailer shares the investment costs of the co-operative and the 3PL service provider. In this case, for the green investment cost of the co-operative, the retailer bears the proportion of u and the co-operative bears $1-u$. For the freshness investment cost of the 3PL service provider, the retailer bears the proportion of v, and the 3PL service provider bears $1-v$ (where $0 < u+v < 1$). At this point, the benefit functions of the co-operative, slaughtering and processing enterprise, 3PL service provider, and retailer are as follows. The cost-sharing contract is denoted by superscript CS.

$$\Pi_s^{SCS} = (w - c_s + g_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}(1-s_0)(1-u)\alpha g_r^2 \tag{81}$$

$$\Pi_m^{SCS} = (p_m - w - c_m)(a - \lambda p + \mu g_r + \eta f_r) \tag{82}$$

$$\Pi_r^{SCS} = (p - p_m - p_l - c_r)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}u(1-s_0)\alpha g_r^2 - \frac{1}{2}v\beta f_r^2 \tag{83}$$

$$\Pi_l^{SCS} = (p_l - c_l)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}(1-v)\beta f_r^2 \tag{84}$$

The optimal decision is found as follows:

$$g_r^{SCS^*} = \frac{\beta(\lambda+\mu)(1-v)(\lambda c_m + \lambda c_r + \lambda c_l + \lambda c_s - a)}{(4\alpha\eta^2 - 16\alpha\lambda\beta)(1-u)(1-s_0) + \beta(\lambda+\mu)^2(1-v) + 16\alpha\beta\lambda v(1-s_0)(1+u)(1-s_0)} \tag{85}$$

$$w^{SCS^*} = \frac{A_1(\lambda c_m + \lambda c_r + \lambda c_l - a) + A_2(\lambda c_m + \lambda c_r + \lambda c_l - \lambda c_s - a) - \beta\lambda\mu^2(1-v)c_s}{\lambda[4\alpha\eta^2 - 16\alpha\lambda\beta)(1-u)(1-s_0) + \beta(\lambda+\mu)^2(1-v) + 16\alpha\beta\lambda v(1-s_0)(1+u)(1-s_0)]} \tag{86}$$

$$A_1 = \beta\lambda^2(v-1) \tag{87}$$

$$A_2 = 8\alpha\lambda\beta(1-u)(1-v)(1-s_0) - 2\alpha\eta^2(1-u)(1-s_0) - \beta\lambda\mu(1-v) \tag{88}$$

$$p_m^{SCS^*} = \frac{a + \mu g_r^{SCS^*} + \lambda w^{SCS^*} + \lambda c_m - \lambda c_r - \lambda c_l}{2\lambda} \tag{89}$$

$$f_r^{SCS^*} = \frac{\eta\left(a + \mu g_r^{SCS^*}\right) - \lambda\eta(p_m^{SCS^*} + c_r + c_l)}{4\lambda\beta - \eta^2 - 4\lambda\beta v} \tag{90}$$

$$p_l^{SCS^*} = \frac{2\beta(a + \mu g_r^{SCS^*})(1-v)\Big) - 2\lambda\beta(p_m^{SCS^*} + c_r - c_l)(1-v)\Big) - \eta^2 c_l}{4\lambda\beta - \eta^2 - 4\lambda\beta v} \tag{91}$$

$$p^{SCS^*} = \frac{a + \mu g_r^{SCS^*} + \eta f_r^{SCS^*} + \lambda(p_m^{SCS^*} + p_l^{SCS^*} + c_r)}{2\lambda} \tag{92}$$

Substituting the above optimal solutions into the respective benefit functions yields:

$$\begin{aligned}\Pi_s^{SCS^*} = {} & (w^{SCS^*} - c_s)(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) \\ & -\tfrac{1}{2}(1-s_0)(1-u)\alpha(g_r^{SCS^*})^2\end{aligned} \tag{93}$$

$$\Pi_m^{SCS^*} = (p_m^{SCS^*} - w^{SCS^*} - c_m)(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) \tag{94}$$

$$\begin{aligned}\Pi_r^{SCS^*} = {} & (p^{SCS^*} - p_m^{SCS^*} - p_l^{SCS^*} - c_r)(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) \\ & -\tfrac{1}{2}u(1-s_0)\alpha\left(g_r^{SCS^*}\right)^2 - \tfrac{1}{2}v\beta\left(f_r^{SCS^*}\right)^2\end{aligned} \tag{95}$$

$$\Pi_l^{SCS^*} = (p_l^{SCS^*} - c_l)(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) - \frac{1}{2}(1-v)\beta\left(f_r^{SCS^*}\right)^2 \tag{96}$$

$$\begin{aligned}\Pi_{En}^{SCS^*} = {} & (p^{SCS^*} - c_l - c_r - c_m - c_s)(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) \\ & -\tfrac{1}{2}(1-s_0)\alpha(g_r^{SCS^*})^2 - \tfrac{1}{2}\beta(f_r^{SCS^*})^2\end{aligned} \tag{97}$$

$$\Pi_{El}^{SCS^*} = (a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) g_r^{SCS^*} \tag{98}$$

$$\begin{aligned}\Pi_{TR}^{SCS^*} = {} & (p^{SCS^*} - c_l - c_r - c_m - c_s + g_r^{SCS^*})(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) \\ & -\tfrac{1}{2}(1-s_0)\alpha(g_r^{SCS^*})^2 - \tfrac{1}{2}\beta(f_r^{SCS^*})^2\end{aligned} \tag{99}$$

$$\begin{aligned}SW^{SCS^*} = {} & (p^{SCS^*} - c_l - c_r - c_m - c_s + g_r^{SCS^*})(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*}) \\ & -\tfrac{1}{2}(1-s_0)\alpha(g_r^{SCS^*})^2 - \tfrac{1}{2}\beta(f_r^{SCS^*})^2 + \tfrac{1}{2}(a - \lambda p^{SCS^*} + \mu g_r^{SCS^*} + \eta f_r^{SCS^*})^2\end{aligned} \tag{100}$$

4.1.2. Numerical Analysis

Based on the values of relevant parameters in Table 2, when $u = 0.1$ and $v = 0.1$, it is measured that the cost-sharing contract can achieve the coordination of interests in the green supply chain. The optimal decision-making and optimal benefits of decentralized decision-making and cost-sharing contracts under the co-operative-led operation mode are shown in Table 4.

As can be seen from Table 4, under the cost-sharing contract, the economic benefits, ecological benefits, and total benefits of the green supply chain of livestock products have been improved. The cost-sharing contract is able to achieve the coordination of interests in the green supply chain of livestock products to a certain extent. The reason is that the participating subjects of the green supply chain of livestock products also share certain risks while bearing costs. Co-operatives, as the main body of breeding, may face risks in the process of breeding, including livestock and poultry diseases, weather disasters, market price fluctuations, etc., and the production risk they bear in production is much higher than that of other main bodies in the green supply chain. Through the cost-sharing contract, it can motivate the co-operatives to pay more attention to green development and adopt more environmental protection measures and quality management measures in the production

process. At the same time, it can promote the co-operation and the establishment of a close interest linkage mechanism in the green supply chain of livestock products.

Table 4. Optimal decision-making and optimal benefits of decentralized decision-making and cost-sharing contracts under co-operative leadership.

	Operation Mode Led by Co-Operatives	
	Decentralized Decision-Making	**Cost-Sharing Contract**
g_r	11.88	18.60
f_r	2.36	2.77
p	58.53	54.33
p_l	10.95	10.97
p_m	41.85	41.86
w	22	21.21
Π_s	213.69	225.34
Π_m	150	167.16
Π_r	23	31.02
Π_l	75.48	83.52
Π_{En}	331.89	344.95
Π_{El}	131.49	162.15
Π_{Tr}	463.38	507.10
SW	504.38	731.97

4.2. Design Contract for Coordination of Interests in Green Supply Chain of Livestock Products Led by Slaughtering and Processing Enterprises

4.2.1. Benefit-Sharing Contract

In this operation mode, the slaughtering and processing enterprise invests in the greenness of livestock products, and the 3PL service provider invests in the freshness. To make the optimal decision-making level under the decentralized decision-making scenario reach the level under the centralized decision-making scenario, the investment costs of the greenness and freshness of livestock products will increase, and the costs of the slaughtering and processing enterprise and the 3PL service provider will increase, and the profit margins will be further reduced.

Therefore, both parties can consider sharing the profits of the co-operative. The proportion of the profits of the co-operative shared by the slaughtering and processing enterprise and the 3PL service provider is u and v, respectively ($0 < u + v < 1$), and the co-operative accounts for the proportion of $1 - u - v$. At this time, the benefit functions of the co-operative, slaughtering and processing enterprise, the 3PL service provider, and the retailer are as follows. The benefit-sharing contract is denoted by superscript IC.

$$\Pi_s^{MIC} = (1 - u - v)[(w - c_s)(a - \lambda p + \mu g_r + \eta f_r)] \tag{101}$$

$$\begin{aligned}\Pi_m^{MIC} = {} & (p_m - w - c_m + s_m g_r + g_r)(a - \lambda p + \mu g_r + \eta f_r) - \tfrac{1}{2}\alpha g_r^2 \\ & + u[(w - c_s)(a - \lambda p + \mu g_r + \eta f_r)]\end{aligned} \tag{102}$$

$$\Pi_r^{MIC} = (p - p_m - p_l - c_r)(a - \lambda p + \mu g_r + \eta f_r) \tag{103}$$

$$\Pi_l^{MIC} = (p_l - c_l)(a - \lambda p + \mu g_r + \eta f_r) - \frac{1}{2}\beta f_r^2 + v[(w - c_s)(a - \lambda p + \mu g_r + \eta f_r) \tag{104}$$

The optimal decision is solved as follows:

$$g_r^{MIC^*} = \frac{\beta(1 - v)(\lambda + \mu + \lambda s_m)(\lambda c_m + \lambda c_r + \lambda c_l + \lambda c_s - a)}{[(4\alpha\eta^2 - 16\alpha\beta\lambda) + \beta(\lambda + \mu)^2 + \beta\lambda^2 s_m^2 + 2\beta\lambda s_m(\lambda + \mu)](1 - v) - (2\alpha\eta^2 - 8\alpha\beta\lambda)u} \tag{105}$$

$$w^{MIC^*} = \frac{a + \mu g_r^{MIC^*} - \lambda(c_s + c_l + e - c_r) - 2\lambda v c_s}{2\lambda(1 - v)} \tag{106}$$

$$f_r^{MIC^*} = \frac{\eta(a + \mu g_r^{SIC^*}) - \lambda\eta(p_m^{SIC^*} + c_r + c_l) + \lambda\eta v(w^{MIC^*} - c_s)}{4\lambda\beta - \eta^2} \tag{107}$$

$$p_l^{MIC^*} = \frac{2\beta(a + \mu g_r^{MIC^*}) - 2\lambda\beta(p_m^{MIC^*} + c_r) + (\eta^2 - 2\lambda\beta)(vw^{MIC^*} - vc_s + c_l)}{4\lambda\beta - \eta^2} \tag{108}$$

$$p^{MIC^*} = \frac{a + \mu g_r^{MIC^*} + \eta f_r^{MIC^*} + \lambda(p_m^{MIC^*} + p_l^{MIC^*} + c_r)}{2\lambda} \tag{109}$$

Substitute the above optimal decisions into each benefit function:

$$\Pi_s^{MIC^*} = (1 - u - v)[(w^{MIC^*} - c_s)(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*})] \tag{110}$$

$$\begin{aligned}\Pi_m^{MIC^*} &= (p_m^{MIC^*} - w^{MIC^*} - c_m + s_m g_r^{MIC^*} + g_r^{MIC^*})(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) \\ &- \tfrac{1}{2}\alpha(g_r^{MIC^*})^2 + u[(w^{MIC^*} - c_s)(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*})]\end{aligned} \tag{111}$$

$$\Pi_r^{MIC^*} = (p^{MIC^*} - p_m^{MIC^*} - p_l^{MIC^*} - c_r)(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) \tag{112}$$

$$\begin{aligned}\Pi_l^{MIC^*} &= (p_l^{MIC^*} - c_l)(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) - \tfrac{1}{2}\beta(f_r^{MIC^*})^2 \\ &+ v[(w^{MIC^*} - c_s)(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*})]\end{aligned} \tag{113}$$

$$\begin{aligned}\Pi_{En}^{MIC^*} &= (p^{MIC^*} - c_l - c_r - c_m - c_s + s_m g_r^{MIC^*})(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) \\ &- \tfrac{1}{2}\alpha(g_r^{MIC^*})^2 - \tfrac{1}{2}\beta(f_r^{MIC^*})^2\end{aligned} \tag{114}$$

$$\Pi_{El}^{MIC^*} = (a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) g_r^{MIC^*} \tag{115}$$

$$\begin{aligned}\Pi_{TR}^{MIC^*} &= (p^{MIC^*} - c_l - c_r - c_m - c_s + s_m g_r^{MIC^*})(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) \\ &- \tfrac{1}{2}\alpha(g_r^{MIC^*})^2 - \tfrac{1}{2}\beta(f_r^{MIC^*})^2 + g_r^{MIC^*}(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*})\end{aligned} \tag{116}$$

$$\begin{aligned}SW &= (p^{MIC^*} - c_l - c_r - c_m - c_s + s_m g_r^{MIC^*})(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) \\ &- \tfrac{1}{2}\alpha(g_r^{MIC^*})^2 - \tfrac{1}{2}\beta(f_r^{MIC^*})^2 + g_r^{MIC^*}(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*}) \\ &+ \tfrac{1}{2}(a - \lambda p^{MIC^*} + \mu g_r^{MIC^*} + \eta f_r^{MIC^*})^2\end{aligned} \tag{117}$$

4.2.2. Numerical Analyses

Based on the values of relevant parameters in Table 2, when $u = 0.1$ and $v = 0.1$, it is measured that the benefit-sharing contract can realize the coordination of benefits in the green supply chain of livestock products. The optimal decisions and optimal benefits under the decentralized decision-making and benefit-sharing contract in the operation mode led by slaughtering and processing enterprises are shown in Table 5.

Table 5 shows that after the coordination of the benefit-sharing contract, the benefits of each participant are greater than the value of decentralized decision-making, and the benefit-sharing contract can closely link the interests of each participant, motivate the active participation of all parties by sharing economic rewards, and promote the in-depth co-operation among partners to form a more stable and long-term co-operative relationship. Table 5 also shows that when the dominant enterprise considers the ecological benefits, the other participants in the green supply chain are always willing to accept the benefit-sharing contract, and can achieve the Pareto improvement of the economic, ecological, and total benefits of the green supply chain of livestock products under this contract.

Table 5. Optimal decision-making and optimal benefits of decentralized decision-making and benefit-sharing contracts led by slaughtering and processing enterprises.

	Operation Mode Led by Slaughtering and Processing Enterprises	
	Decentralized Decision-Making	**Benefit-Sharing Contract**
g_r	13.87	15.07
f_r	2.41	2.55
p	57.76	54.82
p_l	11.15	9.74
p_m	40.79	41.83
w	20.11	23.97
Π_s	157.08	164.99
Π_m	217.99	236.96
Π_r	40.72	48.12
Π_l	78.54	92.81
Π_{En}	377.17	405.26
Π_{El}	117.16	137.62
Π_{Tr}	494.33	542.88
SW	549.59	701.74

5. Conclusions and Management Insights

5.1. Conclusions

Based on the background of government subsidy, this paper constructs a four-level green supply chain of livestock products consisting of co-operatives, slaughtering and processing enterprises, 3PL service providers, and retailers, adopts the Stackelberg game model to study the optimal product greenness and freshness decisions and the total benefits of the green supply chain under the two operation modes, and designs the cost-sharing and benefit-sharing contract to coordinate the supply chain. The following conclusions are obtained:

(1) The freshness sensitivity factor, the greenness sensitivity factor, and the government subsidy factor all have a positive impact on the green supply chain of livestock products. The greenness, freshness, market demand, and benefits of each subject in the green supply chain of livestock products under two operation modes all increase with the increase in the above three factors. Accompanied by the rising sensitivity of consumers to the freshness and greenness of agricultural products, their demands for products are becoming higher and higher. In order to better meet the needs of consumers, enterprises are bound to increase the investment in product costs to promote the level of greenness and freshness. Due to the continuous improvement of product quality, the market demand will be promoted, so that the benefits of the whole green supply chain of livestock products will be enhanced.

(2) Compared with the co-operative-led operation mode, the slaughtering and processing enterprise-led operation mode has a higher degree of greenness and freshness of livestock products, the benefits of each participating body in the green supply chain of livestock products. From the perspective of the overall development of the green supply chain, the operation mode led by slaughtering and processing enterprises is more favorable to the long-term development of the green supply chain of livestock products.

(3) Compared with decentralized decision-making, the benefit-sharing and cost-sharing contract both increase the greenness and freshness of livestock products and significantly reduce the retail price of livestock products, which increases the total benefits of the co-operatives, slaughtering and processing enterprises, 3PL service providers, and retailers. Therefore, the benefit-sharing and cost-sharing contract are of great significance in coordinating and optimizing the four-level green supply chain of livestock products and improving the efficiency of its benefit distribution.

5.2. Management Insights

Based on the above research conclusions, this article proposes some valuable management insights for different types of supply chain participants, as follows:

(1) From the perspective of co-operatives, as an important force in the coordinated development of the green supply chain of livestock products, co-operatives should rationally pursue the dominant position in the green supply chain of livestock products. They should take advantage of their own strengths to actively promote the green advantages of livestock products, and through organizing publicity activities, carrying out knowledge popularization and other means, let more consumers understand livestock products, and improve consumers' awareness and acceptance of green livestock products. They also need to strengthen interaction and communication with consumers, understand their market needs and preferences through market research, and enhance their trust and loyalty to green livestock products. Additionally, they need to strengthen co-operation with scientific research institutions, universities and other units, introduce advanced green technologies and equipment, actively strive to improve the innovation efficiency of green technologies, and promote the upgrading and transformation of the green supply chain of livestock products. At the same time, they need to strengthen the internal management and training of co-operatives to enhance the green awareness and skill level of organizational members and ensure the effective application and promotion of green technologies.

(2) From the perspective of slaughtering and processing enterprises, slaughtering and processing enterprises should give full play to their dominant advantages in the green supply chain of livestock products. They should ensure the reasonable use of downstream sales channels, and establish stable co-operative relations with downstream retailers to ensure smooth sales channels. At the same time, they need to actively expand diversified sales channels and develop online sales channels, such as e-commerce platforms and social media, to expand the sales network. Additionally, they need to increase investment in green R&D, introduce advanced slaughtering and processing equipment and technology, and improve the quality and added value of green livestock products; strengthen brand building, understand consumer demand through market research, formulate targeted marketing strategies and build corporate brand image; establish a close interest linkage mechanism, such as order co-operation, stock co-operation, industrial alliances, etc., establish co-operative relationships with upstream and downstream entities as well as industry university research institutions, achieve technical support and information sharing, and promote coordinated development of animal husbandry.

(3) From the government's point of view, in order to better enhance the greenness of livestock products in the market and the total benefits of the green supply chain of livestock products, the government should strengthen the subsidies for the upstream breeding main body, encourage and support the breeding main body to adopt more environmentally breeding methods, and enhance the greenness of livestock products from the source. At the same time, it is also necessary to strengthen the subsidies for slaughtering and processing enterprises, such as implementing tax incentives, setting up a special fund to support green R&D of enterprises, and providing subsidies for green equipment, so as to enhance the mobility of enterprises. They also need to guide slaughtering and processing enterprises to carry out in-depth co-operation with scientific research institutions, universities and so on, to jointly research and develop new technologies and products, to promote technological progress and industrial upgrading, and provide financial support to promote the in-depth integration of industry, academia, and research. In addition, the government also needs to pay attention to the market status of the relationship between enterprises, to build fair competition in the market environment, and to avoid the formation of a monopoly in the market of certain subjects in the green supply chain of livestock products. At the same time, the government can also guide enterprises to establish industrial

consortiums or livestock industry associations to promote the development of the green supply chain of livestock products in the direction of centralized decision-making, so as to realize the sharing of resources and improve the overall efficiency of the green supply chain of livestock products.

Author Contributions: Conceptualization, J.Z.; Data curation, J.Z.; Formal analysis, J.Z.; Investigation, J.Z. and M.W.; Methodology, M.W.; Software, M.W.; Visualization, M.W.; Writing—original draft, M.W.; Writing—review and editing, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key R&D Program of China under grant number 2021YFE0190200, National Natural Science Foundation of China (NSFC) under grant number 72163025, Program for Improving the Scientific Research Ability of Youth Teachers of Inner Mongolia Agricultural University under grant number BR220201, Program for Young Talents of Science and Technology in Universities of Inner Mongolia Autonomous Region under grant number NJYT22035, and the Natural Science Foundation of Inner Mongolia Autonomous Region under grant number 2021MS07022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors are grateful to the anonymous reviewers and editorial team for their constructive comments on the study.

Conflicts of Interest: The authors declare no conflicts of interest.

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