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Article

# Differential Strategies of Continuous Agri-Product Supply Chain Considering Consumer Perception of Eco-Quality

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**Abstract:** Considering the influence of the consumers' perception of eco-quality (CPQ) on the dynamic strategies of the continuous agri-product supply chain, the paper examines a two-stage agri-product supply chain composed of a supplier and a retailer, where the supplier invests in eco-quality improvement and the retailer invests in advertising. Taking the CPQ, eco-quality and goodwill as ternary state variables, the paper formulates joint decision-making models of a continuous agri-product supply chain based on differential game theory. The paper has analyzed equilibrium strategies in decentralized and centralized scenarios, respectively, and further developed an advertising–eco-quality investment cost-sharing contract to coordinate the supply chain. Finally, comparative and numerical analyses have been conducted. The analyses results reveal that consumers' perceptions of eco-quality and their goodwill preference towards an agri-product encourage the supplier and retailer to improve the eco-quality of the agri-product and the level of advertising. Indeed, the greater the impact of goodwill on demand, the higher level of the supplier's eco-quality investment and the retailer's advertising effort, and the higher the profits of the supply chain. The paper also finds that the proposed cost-sharing contract can achieve a Pareto improvement in the continuous agri-product supply chain system. Furthermore, the higher the consumer goodwill preference, the more motivated suppliers and retailers are to cooperate.

**Keywords:** continuous agri-product; consumer perception; eco-quality; differential game; cost-sharing contract

**MSC:** 90C99



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## 1. Introduction

Due to the continuous improvement in living standards and people's increasing awareness of health, consumers are very sensitive to the eco-quality of agri-products, such that more and more consumers tend to purchase agri-products with a higher eco-quality [1–3]. Different to seasonal agri-product whose production greatly depends on the seasonal atmosphere, continuous agri-production is less dependent on climate conditions, so they can be grown continuously on a large scale throughout the year. However, plenty of food safety incidents are related to continuous agri-production because of producers' inappropriate quality management, such as the earth pit sauerkraut incident and excessive propylene glycol of MaiQuer in China. Therefore, strict eco-quality control and continuously eco-quality improvement are significantly important for continuous agri-product production [4,5]. The upstream and downstream of the agri-product supply chain often continue to strengthen quality investments throughout a product's life cycle to meet the growing ecological consumption needs of consumers. Indeed, consumers dynamically perceive the eco-quality of agri-product through information such as branding, advertising and quality labels to make purchasing decisions [6]. In the agri-product supply chain, suppliers strive to improve the eco-quality of agri-products, such as New Hope Liuhe, and have created smart farming systems to manage the eco-quality throughout a product's life cycle. Furthermore, suppliers or retailers often guide consumers to become concerned about and purchase ecological agri-products through media channels such as advertisements, e.g., Wen's Broiler promotes its green and ecological development concept through TV, radio, short videos and live streaming. Therefore, considering consumers' perceptions of eco-quality, it is worth investigating the joint quality and marketing decisions of the continuous agri-product supply chain to improve the eco-quality of continuous agri-products and enhance supply chain performance.

Recently, eco-quality improvement has been a popular research topic in the field of agricultural supply chain management. Yu et al. [7] studied the price decision-making and coordination mechanism of the agri-product supply chain, considering the quality evaluation of agri-products. Zeng [8] proposed an optimization path for the quality coordination control of the agri-product supply chain. Zhang et al. [9] constructed a whole process supply chain quality evaluation system of agri-product cold chain logistics based on fuzzy AHP. As the static model ignores the long-term dynamics features of agricultural production and operation, scholars began analyzing the quality improvement of agri-product based on a dynamic framework. Besik et al. [10] designed the quality attenuation function of agri-products, and studied the supply strategy of agri-products considering the ability of producers under the market competition of origin by using the differential game method. Chen [11] constructed a game-based model for manufacturers and retailers to implement agri-product quality grading, and found that retailers' quality grading could maximize the profits of an agri-product supply chain system. Qin et al. [12] constructed a game model of bilateral quality effort decision-making of agri-products, and analyzed the impact of the dynamic evolution of altruism and reciprocity of supermarkets on the level of bilateral quality effort. The above studies focus on the quality control of the production link, but ignore the impact of the marketing strategies of agri-product retailers on the quality decisions of upstream suppliers.

Consumer perceptions of quality greatly impact the operation of the agri-product supply chain. Feng and Guo [13] established a supply chain model of poverty-alleviating agri-products considering the quality perception of consumers, and explored the impact of introducing poverty-alleviating agri-products with different quality levels on the equilibrium results of the supply chain. Irmansyah et al. [14] designed an optimization model for the supply chain of agri-products aiming at changes in the perceived consumer value during COVID-19, taking the Bandung agri-product market as the object. Yang et al. [15] introduced the reference effect of consumers on the freshness of dairy products into the dual-channel dairy-product supply chain, with a third-party logistics service provider participating, and explored the impact of the reference effect of freshness on the dairy product supply chain based on a differential game model. The above studies emphasize the importance of consumer quality perception to the operation of the agri-product supply chain, but ignores the dynamic evolution characteristics of consumer perceptions of eco-quality, and does not discuss the important impact of the evolution process of consumer quality perception on the agri-product supply chain.

A retailer's advertising is crucial for the promotion of ecological agri-products. Li et al. [16] proposed that cooperative advertising can coordinate the dual-channel supply chain, which is conducive to achieving a win-win situation for both online and offline channels. Taboubi [17] studied the pricing and advertising of supply chain enterprises in a dynamic environment. Chen et al. [18] developed a decision-making model for online and offline advertising in a dual-channel supply chain, and proposed that supporting advertising can achieve a Pareto improvement in the dual-channel supply chain. Advertising is equally important to the agri-product supply chain. Huang et al. [19] analyzed the transfer mechanism of agri-product brand value from the perspective of an industrial value chain, and proposed that agri-product brand-image building can be strengthened from the aspects of brand value elements, brand value innovation and advertising. Li et al. [20] hypothesized that the reputation of agri-products was jointly affected by supermarket advertising and the consumer reference quality effect, and found that the consumer reference quality effect could encourage rural cooperatives to improve the quality of agri-products and alleviate the advertising pressure of supermarkets. In the process of advertising marketing, the behavior of consumers, retailers, suppliers and other supply chain members will change dynamically, but few studies have explored the comprehensive impact of the dynamic behavior of supply chain members on the operation of agricultural product supply chains.

Overall, the previous literature has deeply analyzed agri-product quality management, consumer quality perception, and advertising and marketing. However, few studies have examined the impact of the dynamic changes in these factors on the operational decision-making of the agri-product supply chain simultaneously. The existing studies related to agri-product supply chain management ignore some fundamental issues, such as how the CPQ of agri-products affects the operational strategies of continuous agri-product supply chains, or how to improve the performance of a continuous agri-product supply chain with a consideration of CPQ. To answer these questions, the paper intends to investigate the dynamic strategies of the continuous agri-product supply chain based on a dynamic framework. In view of this, the paper takes eco-quality, consumer quality perception and goodwill as state variables and formulated a dynamic joint decision-making model of continuous agri-product supply chains based on a differential game model. The equilibrium strategies and profit of the continuous agri-product supply chain under centralized and decentralized scenarios are discussed. Furthermore, the paper proposes a cost-sharing-based contract to coordinate the supply chain and the comparative analysis results suggest the proposed contract can achieve a Pareto improvement of the supply chain.

## 2. Literature Review

As the key link in agricultural supply chain management, whether consumers buy agri-products has an important impact on the circulation efficiency of the agricultural supply chain [21,22]. Regarding consumers' agri-product purchasing behavior, scholars have conducted in-depth studies mainly from two perspectives: the influence of consumers' preferences on their purchasing behavior [23–28] and the external factors that affect consumers' purchasing behavior [29–34]. The quality of agri-products and consumers' perception of quality are important factors affecting consumers' decisions to purchase agri-products [35,36].

Scholars mainly establish static decision-making models to put forward strategies of quality improvement of agri-products. Ma and Zhang established a game model to ensure the agricultural products' quality and safety, and on the basis of the analysis model, proposed measures to protect the agricultural products' quality and safety [37]. Prashar et al. proposed a blockchain-based solution that is an important mechanism for quality control that ensures sufficient food supply chain product safety [38]. To solve the supply quality problems of fresh agri-foods, Xu et al. deeply studied decision-making behavior on the supply quality of agri-foods in the e-supply chain using game theory [39]. Bhutta and Ahmad developed a secure monitoring and reporting system based on IoT to update the quality of perishables [40]. Zhao et al. found that internal integration and supplier integration are key factors to improve product quality in the context of the agricultural supply chain [35]. Negi and Trivedi explored factors that impact the quality of fresh produce in the transportation phase of the supply chain and the mitigation framework for improving quality to curb losses [41]. Zhang assessed the traceability assessed the traceability of a blockchain-based agri-product supply chain, as well as constructed a trusted computing model to improve the quality supervision system of agri-products [42].

Scholars began extending the quality improvement of agri-products to a dynamic framework. Su et al. used the dynamic evolutionary game model and multi-agent modeling and simulations to discussed the key factors required to maintain the quality and safety of agri-products [43]. Yang et al. built an evolutionary game model and employed the replicated dynamic equation to study the evolutionarily stable strategies of suppliers and producers, and propose strategies to improve food quality [44]. Feng et al. found blockchain-based WSN monitoring can achieve the continuous monitoring of dynamic indicators and improve the quality and safety management of frozen shellfish during cold storage [45]. Using the Behrman continuous dynamic programming theory, Li et al. showed that consumers' altruistic preference behaviors have an important incentive effect on the improvement in the quality of agri-products [46]. Zhu et al. built a circulation information system for agri-products based on the internet of things to ensure the quality and safety of agri-products [47]. Kappelman and Sinha considered a dynamic food supply chain with multiple process steps and used big data mining techniques to study the effect of management decisions on the quality of the final product [48]. Mishra et al. considered the marginal reduction cost for limiting carbon emissions, flexible production to meet fluctuating demand, and continuous investment to improve product quality [49]. Our research is also based on dynamic models; however, different to the above studies that only focus on quality improvement in the production stage of the agri-product supply chain, this paper further analyzes the impact of the marketing strategies of retailers on the quality decisions of upstream suppliers.

The consumer perception of quality is an important factor affecting the operational decisions of the agri-product supply chain [50,51]. It is significant to correctly view and utilize consumers' perception of quality to improve the performance of the agri-product supply chain [52]. Zheng et al. studied consumer's online grocery shopping preferences and shed light on policy and regulation design and implementation in the e-commerce industry [53]. Wang et al. evaluated Chinese consumers' trust in food certification, and incorporated perceived quality as a new construct into the theory of planned behavior to further analyze their intention to purchase certified food [54]. Okpiaifo et al. assessed Nigerian consumers' perception of the SRP sustainability indicators, and the results show that consumers have a strong preference for sustainability indicators associated with food safety and health and safety [55]. Hobbs showed that consumers' underlying food values may shape their response to uncertainty during a pandemic [56]. Cao et al. strengthened trust in the cross-border beef supply chain between Australia and China from a consumer perspective based on a blockchain-based supply chain implementation [57]. Brandtner et al. gathered and analyzed consumer satisfaction data and sentiments available on the open web, and evaluated the impact of COVID-19 on consumer satisfaction at the PoS [58]. Sarkar et al. developed a green supply chain management strategy with less pollution for biodegradable products and included an outsourcing strategy only to control the quality of the finished bio-products which would be delivered to the multi-retailer [59]. However, these studies do not integrate the dynamic evolving nature of consumer quality perception with its impact on the agri-product supply chain.

In addition to the production stage of the agri-product supply chain, retailers' marketing strategies also have a significant impact on the quality decisions of suppliers [60,61]. Particularly, advertising is one of the retailer's marketing strategies [62]. Chutani and Sethi modeled a Stackelberg differential game and found that the Nash game between the retailers determines their optimal advertising efforts for the products they sell in response to manufacturers' decisions [63]. Tanwari found the relationship between green advertising and brand loyalty is significantly but negatively moderated by green supply chain practices [64]. Collins and Galbraith discussed the problem of advertising investment in a dual-channel supply chain consisting of traditional retail channels and online electronic direct sales channels [65]. Mozafari et al. addressed the coordination of pricing and cooperative advertising policies in a two-echelon supply chain under fuzziness of demand function parameters and manufacturing costs [66]. Huang et al. examined the interaction between a retailer's information acquisition and a manufacturer's advertising strategies [67]. Bo et al. formulated a Stackelberg game model to study the cooperative advertising problem by taking price and advertising effects into account and analyzing how profit is influenced by different cooperative advertising strategies [68]. However, these studies rarely discuss the comprehensive impact of advertising and marketing behaviors on the operation of the agri-product supply chain. Further, we have listed the contribution of different authors and our contributions in Table 1.

**Table 1.** Contribution of different authors.

| Author (s) | Quality Effort | Consumer Perception | Marketing Strategy | Coordination Mechanisim | Dynamic Framework |
|---|---|---|---|---|---|
| Ma and Zhang [34] | √ | √ | | | |
| Besik et al. [8] | √ | √ | | | √ |
| Li et al. [14] | | √ | √ | √ | |
| Taboubi [15] | | | √ | √ | √ |
| Yang et al. [41] | √ | | √ | | √ |
| Feng et al. [42] | √ | | | | √ |
| Zheng et al. [50] | | √ | √ | | |
| Taghikhah et al. [24] | √ | √ | √ | | |
| Bhutta and Ahmad [37] | √ | | √ | | √ |
| Negi and Trivedi [38] | √ | | √ | | |
| Bo et al. [65] | | | √ | √ | |
| Zhang and Zhou [7] | √ | | | | |
| This paper | Eco-quality of agri-products | Consumer perception of eco-quality | Advertising | Cost-sharing contract | Differential game based model |

## 3. Problem Description and Assumptions

### 3.1. Notations

The state variables, decision variables and relative parameters adopted in the models are summarized in Table 2.

**Table 2.** Notations.

| | |
|---|---|
| **State variables** | |
| $E(t)$ | agri-product's eco-quality at time $t$, $E(0) = E_0$ |
| $\Theta(t)$ | level of CPQ at time $t$, $\Theta(0) = \Theta_0$ |
| $G(t)$ | goodwill towards ecological agri-products at time $t$, $G(0) = G_0$ |
| **Decision variables** | |
| $I(t)$ | supplier's eco-quality investment effort at time $t$ |
| $A(t)$ | retailer's advertising effort at time $t$ |
| $w(t)$ | wholesale price at time $t$ |
| $p(t)$ | selling price at time $t$ |
| **Parameters** | |
| $t$ | time, $t \geq 0$ |
| $\varepsilon$ | coefficient of suppliers' eco-quality investment efforts on agri-product, $\varepsilon > 0$ |
| $\theta$ | coefficient of the eco-quality of agri-products on CPQ, $\theta > 0$ |
| $\alpha, \beta$ | coefficients of retailer's advertising efforts and CPQ on goodwill, $\alpha, \beta > 0$ |
| $\delta, \tau, \xi$ | natural decay rate of eco-quality of agri-product, CPQ and goodwill, $\delta, \tau, \xi > 0$ |
| $D$ | market demand function of ecological agri-products |
| $a$ | market capacity, $a > 0$ |
| $b$ | price elasticity, $b > 0$ |

**Table 2.** *Cont.*

| **State variables** | |
|---|---|
| $\gamma$ | coefficient of goodwill on demand, $\gamma > 0$ |
| $C_m(t)$, $C_r(t)$ | investment of eco-quality and advertising |
| $K_m$, $K_r$ | coefficients of eco-quality cost and advertising cost, $K_m > 0$, $K_r > 0$ |
| $\rho$ | discount factor, $\rho > 0$ |
| $J$ | long-term profits |
| **subscript** $m, r, s$ | supplier, retailer and supply chain, respectively |
| **superscript** $D, C, S$ | under decentralized, centralized, and cost-sharing contract scenario |

### *3.2. Problem Description*

In the market for ecological agri-products, the CPQ of continuous agri-products changes dynamically due to the external environment and consumers' self-perceptions. Consumers' purchasing behavior is affected by a combination of factors such as the selling price, eco-quality of agri-products, and retailer's reputation. To address the dynamics of consumers' purchasing behavior, this paper examines the dynamic strategies of a supply chain composed of an agri-product supplier and retailer. The agri-product supplier decides on the quality investment and produces ecological agri-products with eco-quality. Furthermore, the retailer obtains the agri-product at a wholesale price and then sells it to the end consumers. In addition, the retailer invests in advertising to increase the goodwill to improve the sale performance of the ecological agri-product.

### *3.3. Basic Assumptions*

**Assumption 1.** *The eco-quality of agri-products depends on the supplier's quality investment effort. It is assumed the agri-products' eco-quality decays with time because of the aging of quality control facilities and iterative updating of quality control technologies. According to previous reference* [18]*, this paper assumes eco-quality changes over time:*

$$\dot{E}(t) = \varepsilon I(t) - \delta E(t) \tag{1}$$

$E(t)$ and $I(t)$ are, respectively, the agri-product's eco-quality and supplier's eco-quality investment effort at time $t$, where $E(0) = E_0$; $\varepsilon > 0$ is the impact of the suppliers' eco-quality investment efforts on the agri-product; $\delta > 0$ is the decline rate of the eco-quality of the agri-product.

**Assumption 2.** *With the promotion of green agri-products, the continuous investment in eco-quality produces agri-products with high eco-quality. With the increasing supply of ecological apri-products, the ecological agri-products are no longer scarce in the market, such that the original ecological advantages of green agri-producst are no longer obvious. Therefore, the CPQ of agri-products will decline over time. According to previous research* [69]*, this paper describes the change process of CPQ of ecological agri-products as:*

$$\dot{\Theta}(t) = \theta E(t) - \tau \Theta(t) \tag{2}$$

$\Theta(t)$ is the level of the *CPQ* at time $t$, where $\Theta(0) = \Theta_0$. $\theta$ is the coefficient of the eco-quality of agri-products on the *CPQ*. $\tau$ is the natural decay rate of the *CPQ*.

**Assumption 3.** *The supplier's eco-quality investment effort and retailer's advertising effort could improve the reputation of ecological agri-products. It is assumed that the goodwill towards ecological* *agri-products is affected by retailers' advertising investments and the CPQ. According to previous research* [70], *it is assumed that the goodwill change process of ecological agri-products is:*

$$\dot{G}(t) = \alpha A(t) + \beta\Theta(t) - \xi G(t) \tag{3}$$

$G(t)$ is the reputation of ecological agri-products at time $t$, where $G(0) = G_0$. $A(t)$ is the retailer's advertising effort at time $t$. $\alpha > 0$ and $\beta > 0$ are the coefficients of the retailer's advertising efforts and the $CPQ$ on the goodwill towards ecological agricultural products. $\xi > 0$ is the natural decay rate of goodwill.

**Assumption 4.** *El Ouardighi* [71] *believes that market demand is affected by price factors and non-price factors, and has constructed a demand function that can be separated and multiplied. Then, the market demand function of ecological agricultural products can be formulated as:*

$$D(G, p) = h(p)f(G) \tag{4}$$

$h(p) = a - bp$ is the price factor, $a > 0$ is the market capacity, and $b > 0$ is the price elasticity. $f(G) = \gamma G(t)$ represents non-price factors, $\gamma > 0$ represents the coefficient of goodwill on demand.

**Assumption 5.** *Suppose that the eco-quality investment $C_m(t)$ and the advertising investment $C_r(t)$ are convex functions of the eco-quality investment effort and the advertising effort, respectively* [72], *that is, $C_m(t) = \frac{K_m}{2}I^2(t)$ and $C_r(t) = \frac{K_r}{2}A^2(t)$. $K_m$ and $K_r$ are coefficients of the eco-quality cost and the advertising cost, and $K_m > 0$ and $K_r > 0$.*

The supplier determines the wholesale price $w(t)$ and eco-quality effort $I(t)$ of the ecological agri-product, and the retailer determines the selling price $p(t)$ and advertising effort $A(t)$. The paper takes the eco-quality $E(t)$, $CPQ$ $\Theta(t)$ and goodwill $G(t)$ as state variables. Therefore, the long-term profits of suppliers, retailers and supply chains are, respectively, structured as follows:

$$\begin{gathered} J_m = \int_0^\infty e^{-\rho t}[w(t)D(t) - C_m(t)]dt \\ J_r = \int_0^\infty e^{-\rho t}[(p(t) - w(t))D(t) - C_r(t)]dt \\ J_s = \int_0^\infty e^{-\rho t}[p(t)D(t) - C_m(t) - C_r(t)]dt \\ \text{s.t. } \dot{\Theta}(t) = \theta E(t) - \tau\Theta(t) \\ \dot{\Theta}(t) = \theta E(t) - \tau\Theta(t) \\ \dot{G}(t) = \alpha A(t) + \beta\Theta(t) - \xi G(t) \end{gathered} \tag{5}$$

The subscripts $m$, $r$ and $s$ represent the supplier, retailer and supply chain, respectively, and $\rho > 0$ is the discount factor.

## 4. Model Analyses

### 4.1. Decentralized Scenario

Under a decentralized scenario, the supplier and retailer of agri-product make decisions with the goal of maximizing their profit. At this time, the supplier and retailer play a Stackelberg game, represented by superscript $D$. The order of decision-making in this scenario is as follows: the supplier first selects the eco-quality effort $I(t)$ and the wholesale price $w(t)$, then the retailer chooses selling price $p(t)$ and advertising effort $A(t)$. Therefore, the decision-making objective functions of the supplier and retailer are as follows:

$$\begin{aligned} \max_{I,w} J_m^D &= \int_0^\infty e^{-\rho t}[w(t)D(t) - C_m(t)]dt \\ \max_{p,A} J_r^D &= \int_0^\infty e^{-\rho t}[(p(t) - w(t))D(t) - C_r(t)]dt \\ \text{s.t. } \dot{\Theta}(t) &= \theta E(t) - \tau\Theta(t) \\ \dot{\Theta}(t) &= \theta E(t) - \tau\Theta(t) \\ \dot{G}(t) &= \alpha A(t) + \beta\Theta(t) - \xi G(t) \end{aligned} \tag{6}$$

**Proposition 1.** *Under a decentralized scenario:*

*(i) The optimal strategies of the supplier and retailer are:* $w^{D*} = \frac{a}{2b}$, $p^{D*} = \frac{3a}{4b}$, $I^{D*} = \frac{2\varepsilon\theta\beta K_1 L_1}{K_m}$, $A^{D*} = \frac{\alpha K_1 L_3}{K_r}$.

*(ii) The trajectories of eco-quality, CPQ and goodwill are* $E^D(t) = E_\infty^D + (E_0 - E_\infty^D)e^{-\delta t}$, $\Theta^D(t) = \Theta_\infty^D + \frac{\theta e^{-\delta t}(E_0 - E_\infty^D)}{\tau-\delta} + H_1 e^{-\tau t}$, $G^D(t) = G_\infty^D + \frac{\theta\beta e^{-\delta t}(E_0 - E_\infty^D)}{(\tau-\delta)(\xi-\delta)} + \frac{\beta H_1 e^{-\tau t}}{\xi-\tau} + H_2 e^{-\xi t}$. $E_\infty^D$, $\Theta_\infty^D$ and $G_\infty^D$ *are the stable values of eco-quality, CPQ and goodwill under a decentralized scenario.*

*(iii) The overall long-term profits of the supplier, retailer and supply chain are:*

$$\begin{cases} J_m^{D*} = 2(\beta\theta L_1 E_0 + \beta L_2\Theta_0 + L_3 G_0)K_1 + \frac{2\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{2\alpha^2 K_1^2 L_3^2}{\rho K_r} \\ J_r^{D*} = (\beta\theta L_1 E_0 + \beta L_2\Theta_0 + L_3 G_0)K_1 + \frac{2\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{\alpha^2 K_1^2 L_3^2}{2\rho K_r} \\ J_s^{D*} = 3(\beta\theta L_1 E_0 + \beta L_2\Theta_0 + L_3 G_0)K_1 + \frac{4\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{5\alpha^2 K_1^2 L_3^2}{2\rho K_r} \end{cases}$$

The proof of Proposition 1 is presented in Appendix A.1.

**Lemma 1.** *(i)* $\frac{\partial I^{D*}}{\partial\varepsilon} > 0$, $\frac{\partial I^{D*}}{\partial\theta} > 0$, $\frac{\partial I^{D*}}{\partial\beta} > 0$, $\frac{\partial I^{D*}}{\partial\gamma} > 0$, $\frac{\partial I^{D*}}{\partial\alpha} = 0$.

*(ii)* $\frac{\partial A^{D*}}{\partial\varepsilon} = \frac{\partial A^{D*}}{\partial\beta} = \frac{\partial A^{D*}}{\partial\theta} = 0$, $\frac{\partial A^{D*}}{\partial\gamma} > 0$, $\frac{\partial A^{D*}}{\partial\theta} > 0$.

From Lemma 1, the goodwill towards an ecological agri-product has a positive impact on the eco-quality investment effort and advertising effort, which would stimulate retailer to increase their advertising investment and encourage the supplier to improve their eco-quality investment. It can be seen that as $\varepsilon$ increases, the supplier would improve its eco-quality effort, so as to improve the eco-quality of the agri-product. As $\theta$ increases, the eco-quality of agri-products has a greater positive impact on the *CPQ*. With the improvement in $\beta$, the level of the *CPQ* can expand its positive impact on the goodwill towards agri-products. It indicates that the *CPQ* has a positive impact on the improvement in the eco-quality of an agri-product. Consumers make purchasing decisions based on their perception of the eco-quality of agri-products, which encourages suppliers to continuously improve its eco-quality effort to meet consumers' high demands for agri-products with a higher eco-quality. At the same time, the increase in the *CPQ* stimulates the improvement in goodwill, which in turn stimulates market demand and, thus, increases the efficiency of the continuous agri-product supply chain. As retailer's advertising effort increases with $\alpha$, indicating positive goodwill will increase a retailer's advertising efficiency. A retailer's advertising has an important influence on the supply chain mainly by influencing goodwill. In a market environment with high advertising efficiency, retailers are more motivated to act as the main promoters of agri-products and, thus, set higher levels of advertising investment. On the other hand, retailers' increased advertising efficiency does not affect the supplier's eco-effort input strategy.

**Lemma 2.** *The trajectory of agri-product's eco-quality $E^D(t)$ shows monotonicity under a decentralized scenario, while the trajectory of the consumers' perception of quality $\Theta^D(t)$ and goodwill $G^D(t)$ are multivariate.*

From Proposition 1(i), it can be seen that when $E_0 - E_\infty^D > 0$, the eco-quality $E^D(t)$ of the agri-product decreases with time $t$, and eventually converges to the stable state $E_\infty^D$; when $E_0 - E_\infty^D < 0$, $E^D(t)$ increases with time $t$, and finally converges to a steady state. However, changes in the *CPQ* $\Theta^D(t)$ show diversity due to the impact of the dynamic eco-quality of the product $E^D(t)$. Similarly, due to the simultaneous impact of the advertising effort $A(t)$ and dynamic *CPQ* $\Theta^D(t)$, the variation in an agri-product's goodwill $G^D(t)$ also shows diversity, which would be also monotonic when $\beta = 0$ and goodwill would not affected by consumers' ecological perceptions.

### 4.2. Centralized Scenario

Under a centralized scenario, the supplier and retailer play a cooperative game with the objective of maximizing the overall profit of the supply chain, denoted by the superscript $C$. At this point, the decision objective function of the ecological agri-product supply chain system is:

$$\begin{aligned} \max_{p,I,A} J_s^C = \int_0^\infty e^{-\rho t}[p(t)D(t) - \tfrac{K_m}{2}I^2 - \tfrac{K_r}{2}A^2]dt \\ \text{s.t. } \dot{\Theta}(t) = \theta E(t) - \tau\Theta(t) \\ \dot{\Theta}(t) = \theta E(t) - \tau\Theta(t) \\ \dot{G}(t) = \alpha A(t) + \beta\Theta(t) - \xi G(t) \end{aligned} \tag{7}$$

**Proposition 2.** *Under a centralized scenario:*

*(i) The optimal strategies of the supply chain are:* $p^{C*} = \frac{a}{2b}$, $I^{C*} = \frac{4\beta\theta\varepsilon K_1 L_1}{K_m}$, $A^{C*} = \frac{4\alpha K_1 L_3}{K_r}$.

*(ii) The trajectories for eco-quality, CPQ and goodwill are:* $E^C(t) = E_\infty^C + (E_0 - E_\infty^C)e^{-\delta t}$, $\Theta^C(t) = \Theta_\infty^C + \frac{\theta e^{-\delta t}(E_0 - E_\infty^C)}{\tau - \delta} + H_3 e^{-\tau t}$, $G^C(t) = G_\infty^C + \frac{\theta\beta e^{-\delta t}(E_0 - E_\infty^C)}{(\tau-\delta)(\xi-\delta)} + \frac{\beta H_3 e^{-\tau t}}{\xi - \tau} + H_4 e^{-\xi t}$ *where* $E_\infty^C = \frac{4\beta\theta\varepsilon^2 K_1 L_1}{\delta K_m}$, $\Theta_\infty^C = \frac{4\beta\theta^2\varepsilon^2 K_1 L_1}{\tau\delta K_m}$, $G_\infty^C = \frac{4\beta^2\theta^2\varepsilon^2 K_1 L_1}{\xi\tau\delta K_m} + \frac{4\alpha^2 K_1 L_3}{\xi K_r}$.

*(iii) The long-term profit of the supply chain system is:* $J_s^{C*} = 4(\beta\theta L_1 E_0 + \beta L_2 \Theta_0 + L_3 G_0)K_1 + \frac{8\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{8\alpha^2 K_1^2 L_3^2}{\rho K_r}$.

### 4.3. Coordination with Cost-Sharing Contract

In order to alleviate channel conflicts and stimulate the retailer to invest in advertising, the supplier usually shares a portion of the advertising costs with retailers. At the same time, since a reduction in the supplier's eco-quality investment costs is conducive to improving an agri-product's eco-quality, the retailer also shares a certain proportion of the investment costs with the supplier to stimulate the supplier to improve eco-quality investment levels. Therefore, this paper will further explore the effectiveness of the advertising–eco-quality investment cost-sharing contract in improving the performance of this agri-product supply chain. Under the cost-sharing contract, the retailer and supplier share the costs of advertising and the eco-quality investment, denoted by the superscript $S$. Suppose $0 \leq \varphi(t) \leq 1$ is the advertising share of the supplier at moment $t$, and $0 \leq \lambda(t) \leq 1$ is the ecological input cost share of the retailer at moment $t$. At this time, the decision-making problems of suppliers and retailers are:

$$\begin{aligned} \max_{w,I,\varphi} J_m^S &= \int_0^\infty \left(e^{-\rho t}(wD(t) - (1-\lambda)\tfrac{K_m}{2}I^2 - \varphi\tfrac{K_r}{2}A^2)\right)dt \\ \max_{p,A,\lambda} J_r^S &= \int_0^\infty \left(e^{-\rho t}((p-w)D(t) - \lambda\tfrac{K_m}{2}I^2 - (1-\varphi)\tfrac{K_r}{2}A^2)\right)dt \\ \text{s.t. } \dot{\Theta}(t) &= \theta E(t) - \tau\Theta(t) \\ \dot{\Theta}(t) &= \theta E(t) - \tau\Theta(t) \\ \dot{G}(t) &= \alpha A(t) + \beta\Theta(t) - \xi G(t) \end{aligned} \tag{8}$$

**Proposition 3.** *Under the cost-sharing contract:*

*(i) The optimal strategies for the supply chain are, respectively:* $w^{S*} = \frac{a}{2b}$, $p^{S*} = \frac{3a}{4b}$, $I^{S*} = \frac{2\varepsilon\theta\beta K_1 L_1}{K_m}$, $A^{S*} = \frac{5\alpha K_1 L_3}{2K_r}$, $\lambda^{S*} = 0$ $\varphi^{S*} = \frac{3}{5}$.

*(ii) The trajectories for eco-quality, the CPQ and goodwill are:* $E^S(t) = E_\infty^S + (E_0 - E_\infty^S)e^{-\delta t}$, $\Theta^S(t) = \Theta_\infty^S + \frac{\theta e^{-\delta t}(E_0 - E_\infty^S)}{\tau-\delta} + H_5 e^{-\tau t}$, $G^S(t) = G_\infty^S + \frac{\theta\beta e^{-\delta t}(E_0 - E_\infty^S)}{(\tau-\delta)(\xi-\delta)} + \frac{\beta H_5 e^{-\tau t}}{\xi-\tau} + H_6 e^{-\xi t}$ *where* $E_\infty^S = \frac{2\beta\theta\varepsilon^2 K_1 L_1}{\delta K_m}$, $\Theta_\infty^S = \frac{2\beta\theta^2\varepsilon^2 K_1 L_1}{\tau\delta K_m}$, $G_\infty^S = \frac{2\beta^2\theta^2\varepsilon^2 K_1 L_1}{\xi\tau\delta K_m} + \frac{5\alpha^2 K_1 L_3}{2\xi K_r}$

*(iii) The overall long-term profits of the supplier, retailer and the supply chain are:*

$$\begin{cases} J_m^{S*} = 2(\beta\theta L_1 E_0 + \beta L_2\Theta_0 + L_3 G_0)K_1 + \frac{2\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{25\alpha^2 K_1^2 L_3^2}{8\rho K_r} \\ J_r^{S*} = (\beta\theta L_1 E_0 + \beta L_2\Theta_0 + L_3 G_0)K_1 + \frac{2\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{5\alpha^2 K_1^2 L_3^2}{4\rho K_r} \\ J_s^{S*} = 3(\beta\theta L_1 E_0 + \beta L_2\Theta_0 + L_3 G_0)K_1 + \frac{4\beta^2\theta^2\varepsilon^2 K_1^2 L_1^2}{\rho K_m} + \frac{35\alpha^2 K_1^2 L_3^2}{8\rho K_r} \end{cases}$$

Proposition 3 shows that under the advertising–eco-quality investment cost-sharing contract, there is an optimal sharing ratio where the supplier bears all the eco-quality investment costs and shares 60% of the advertising costs.

## 5. Comparative Analyses

A comparative analysis of the optimal supply chain strategies and optimal value functions for the three scenarios above leads to the following conclusions:

**Proposition 4.** *The comparison of the optimal equilibrium strategy and the profit of the supply chain under the three modes is as follows:*

*(i)* $p^{C*} < p^{D*} = p^{S*}$, $I^{C*} > I^{D*} = I^{S*}$,$A^{C*} > A^{S*} > A^{D*}$.

*(ii)* $E_\infty^C > E_\infty^D = E_\infty^S$, $\Theta_\infty^C > \Theta_\infty^D = \Theta_\infty^S$,$G_\infty^C > G_\infty^S > G_\infty^D$.

*(iii)* $J_m^{S*} > J_m^{D*}$, $J_r^{S*} > J_r^{D*}$,$J_s^{C*} > J_s^{S*} > J_s^{D*}$.

The proof of Proposition 1 is presented in Appendix A.2. Proposition 4(i) shows that the level of advertising effort is highest under the centralized decision scenario, and consumers will also obtain the highest eco-quality of product at the lowest selling price. The selling price under the decentralized and coordination scenarios are consistent. The level of advertising effort under the coordination scenario is higher than the decentralized scenario. Therefore, under the coordination scenario, the supplier is incentivized to increase the level of advertising effort by sharing the cost of advertising investment, which helps to enhance goodwill and demand for the agri-product.

Propositions 4(i) and (iii) show that the stable values of the eco-quality of an agri-product, the *CPQ* and goodwill, as well as the overall supply chain profits under a centralized scenario are higher than a decentralized one. It suggests that the supply chain under a centralized scenario has the highest efficiency, so the supply chain members should coordinate the agri-product supply chain under a decentralized scenario. Under the advertising–eco-quality investment cost-sharing contract, the overall supply chain profit is less than in the centralized scenario but higher than the decentralized scenario, and the stable value of an agri-product's eco-quality and the *CPQ* are equal to that in the decentralized scenario. Therefore, although the advertising–ecological input cost-sharing contract does not lead to a fully coordinated supply chain, it can achieve a Pareto improvement in the profits of the supplier, retailer and the overall supply chain.

## 6. Numerical Analyses

In order to analyze the impact of important parameters on decision variables and supply chain profits, as well as to compare more intuitively the results under a centralized decision-making scenario, decentralized decision-making scenario and advertising–ecological input cost-sharing contracts, this section is presented in the form of numerical arithmetic examples, referring to the relevant literature [18,73] and setting the values of the relevant parameters in the model as follows: $a = 5$, $b = 2$, $\alpha = 1$, $\beta = 0.8$, $\theta = 0.5$, $\xi = 0.4$, $\varepsilon = 0.8$, $\delta = 0.2$, $\tau = 0.3$, $\rho = 0.3$, $\gamma = 0.8$, $K_m = K_r = 1$, $E_0 = 5$, $\Theta_0 = 10$, and $G_0 = 15$. Table 3 presents the optimal value of the decision variables and the profits of the three scenarios under the different parameter settings of $\beta$ and $\gamma$.

**Table 3.** The optimal value of decision variables and profits under different settings $(\beta, \gamma)$.

| | | $\gamma$=0.6 | | | $\gamma$=0.8 | | | $\gamma$=1 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $\beta$=0.6 | $\beta$=0.8 | $\beta$=1 | $\beta$=0.6 | $\beta$=0.8 | $\beta$=1 | $\beta$=0.6 | $\beta$=0.8 | $\beta$=1 |
| Scenario *D* | $I^{D*}$ | 1.07 | 1.43 | 1.79 | 1.43 | 1.90 | 2.38 | 1.79 | 2.38 | 2.98 |
| | $A^{D*}$ | 0.67 | 0.67 | 0.67 | 0.89 | 0.89 | 0.89 | 1.12 | 1.12 | 1.12 |
| | $p^{D*}$ | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 |
| | $J_m^{D*}$ | 45.08 | 53.27 | 61.88 | 62.29 | 73.86 | 86.19 | 80.58 | 95.88 | 112.35 |
| | $J_r^{D*}$ | 22.75 | 27.59 | 32.85 | 31.52 | 38.63 | 46.49 | 40.87 | 50.59 | 61.48 |
| | $J_s^{D*}$ | 67.83 | 80.85 | 94.72 | 93.80 | 112.49 | 132.68 | 121.46 | 146.46 | 173.83 |
| Scenario *C* | $I^{C*}$ | 2.14 | 2.86 | 3.58 | 2.86 | 3.80 | 4.76 | 3.58 | 4.76 | 5.96 |
| | $A^{C*}$ | 2.68 | 2.68 | 2.68 | 3.57 | 3.57 | 3.57 | 4.46 | 4.46 | 4.46 |
| | $p^{C*}$ | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| | $J_s^{C*}$ | 99.97 | 119.31 | 140.36 | 142.01 | 170.45 | 201.91 | 188.40 | 227.26 | 270.84 |
| Scenario *S* | $I^{S*}$ | 1.07 | 1.43 | 1.79 | 1.43 | 1.90 | 2.38 | 1.79 | 2.38 | 2.98 |
| | $A^{S*}$ | 1.67 | 1.67 | 1.67 | 2.23 | 2.23 | 2.23 | 2.79 | 2.79 | 2.79 |
| | $p^{S*}$ | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 |
| | $J_m^{S*}$ | 46.76 | 54.95 | 63.56 | 65.28 | 76.85 | 89.18 | 85.25 | 100.55 | 117.02 |
| | $J_r^{S*}$ | 23.87 | 28.71 | 33.97 | 33.51 | 40.62 | 48.48 | 43.99 | 53.70 | 64.60 |
| | $J_s^{S*}$ | 70.63 | 83.65 | 97.53 | 98.79 | 117.47 | 137.67 | 129.24 | 154.25 | 181.62 |

It can be seen from Figure 1 that under the three scenarios, the retailer's selling price remains the same with the increase in $\gamma$, while both the level of the supplier's eco-quality investment and retailer's advertising effort increase. The retail price and eco-quality investment are the same under the decentralized and coordination scenarios, and the eco-quality investment and advertising effort under these two scenarios are lower than in the coordination scenario, while the advertising effort is lowest under the decentralized scenario. With the increase in $\gamma$, the supplier and retailer are encouraged to improve the eco-quality and advertising of an ecological agri-product in order to enhance goodwill. Compared to the decentralized scenario, the implementation of the proposed cost-sharing contract results in the same level of eco-quality and a higher level of advertising, suggesting that the sharing of the advertising costs by the supplier can stimulate the retailer to invest more in advertising and contribute to the achievement of a Pareto improvement in the agri-product supply chain.

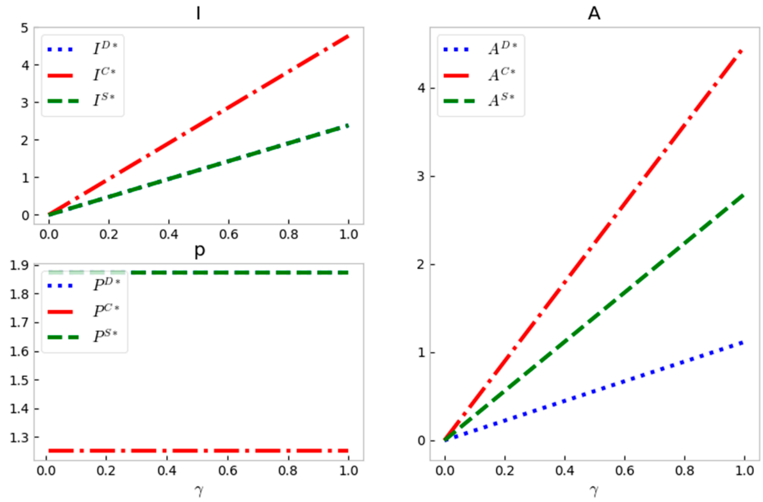


**Figure 1.** Impacts of $\gamma$ on price, ecological effort and advertising effort.

It can be seen from Figure 2 that the profits of the players and the supply chain system increase with the increase in $\gamma$, which indicates that the consumers' stronger goodwill preferences can not only provide incentives for the supplier to improve eco-quality to meet consumers' high requirements for a high-quality agri-product, but also improve the profits of the supply chain. The profit is higher under the coordination scenario than the decentralized scenario, which shows that the proposed cost-sharing contract can achieve Pareto improvements in players and the whole supply chain system. At the same time, the growth rate of the supply chain profits under the coordination scenario is greater with the increase in $\gamma$, which indicates that the improvement efficiency in profits under the coordination scenario is also greater when consumers' goodwill preference is stronger. At the same time, it is conducive to the implementation and promotion of the proposed cost-sharing contracts in the agri-product supply chain.

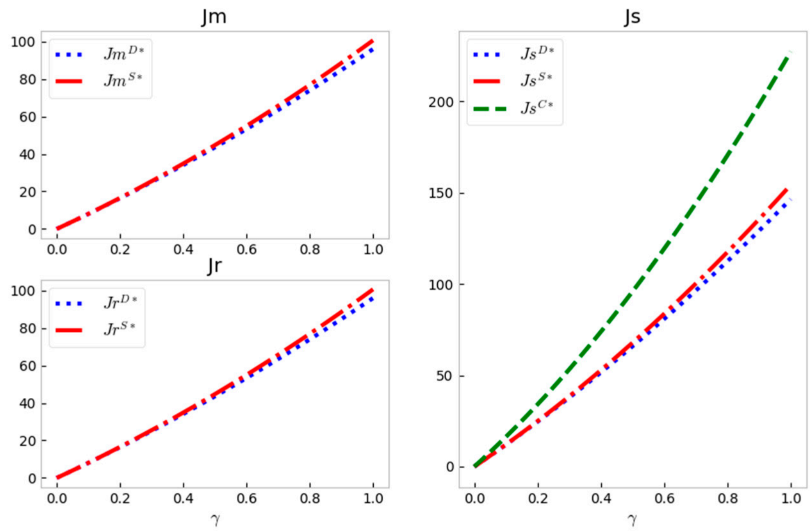


**Figure 2.** Impacts of $\gamma$ on profits.

As can be seen from Figure 3, profits for players and the supply chain system increase with the increase in $\beta$. The demand for an agri-product with high eco-quality expands when consumers are more concerned about eco-quality, such that the profits of players and the supply chain system improve. Furthermore, the profits are higher under the coordination scenario than the decentralized scenario, but the increment of profits are independent of $\beta$. It suggests that the proposed cost-sharing contract can achieve a Pareto improvement in the agri-product supply chain, but $\beta$ is not related to the efficiency of the Pareto improvement.

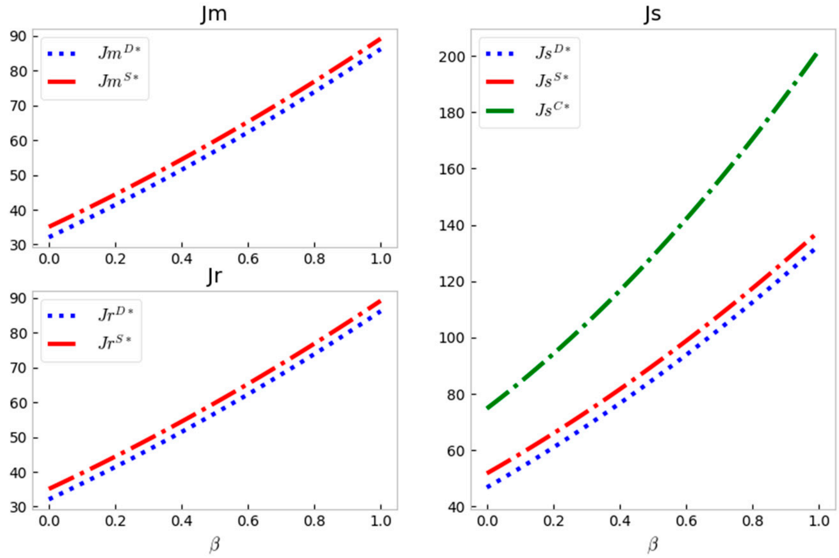


**Figure 3.** Coefficient $\beta$ of impact of consumer ecological perception on goodwill impact on profit.

As can be seen from Figure 4, eco-quality and the goodwill towards the agri-product are continuously improved over time and eventually tend to a stable state. The *CPQ* decreases first, then increases over time when it reaches the minimum level, and finally tends to be stable. This is because the improvement in eco-quality of an agri-product takes time, and consumers will perceive its eco-quality and purchase it only when the eco-quality of an agricultural product has improved to a sufficient level. The steady goodwill is greater under the coordination scenario than the decentralized scenario.

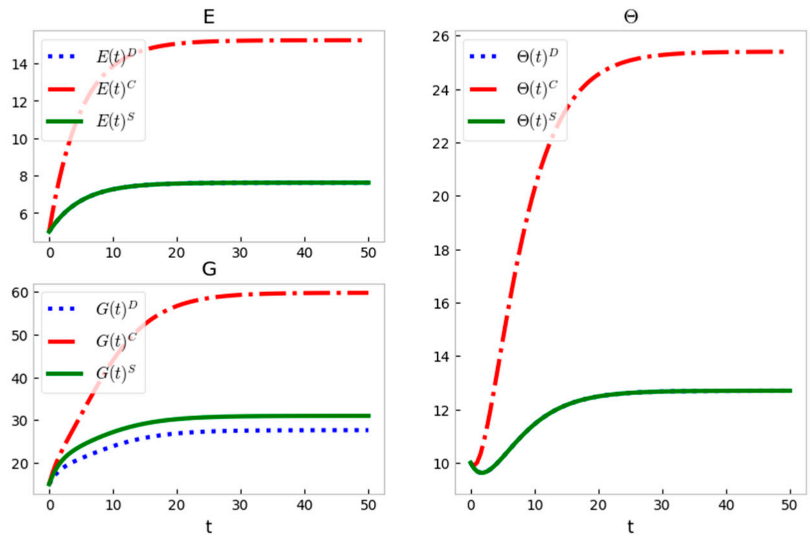


**Figure 4.** Trajectory of eco-quality, consumer ecological perception, and goodwill.

## 7. Conclusions, Managerial Implication and Future Direction

### 7.1. Conclusions

Considering the influence of the *CPQ* on the dynamic strategies of the continuous agri-product supply chain, this paper proposed joint decision-making models based on differential game theory to investigate the optimal dynamic strategies of a centralized and decentralized supply chain. Furthermore, a cost-sharing-based contract was proposed to coordinate the continuous agri-product supply chain. Finally, comparative and numerical analyses were conducted to explore the optimal equilibrium strategies and profits under the three scenarios. The main conclusions are as follows:

(1) The *CPQ* and goodwill preference have positive impacts on the improvement of the eco-quality of an agri-product. The increase in the *CPQ* stimulates an increase in goodwill, which expands consumer demand, and motivates the supplier to continuously improve the eco-quality effort of the agri-product to meet the consumers' high demand for agri-products with high eco-quality.

(2) When the consumers' goodwill preference is strong, the supplier and retailer would improve the eco-quality investment and advertising effort but keep the selling price the same. At this time, the profits for players and the supply chain system would increase.

(3) The proposed advertising–eco-quality investment cost-sharing contract can achieve a Pareto improvement of the continuous agri-product supply chain. It not only improves the eco-quality of an agri-product, but also improves the level of advertising effort. The stronger the consumers' goodwill preference, the greater the efficiency of improvement of the players' profit.

### *7.2. Managerial Implication*

This study also provides certain managerial insights. From the perspective of the suppliers, improving the eco-quality level of continuous agri-products can meet the consumers' demand for agri-products with high eco-quality, so as to obtain the benefits of increasing the price of agri-products, and, thus, realize the growth of economic benefits. Jointly implementing a cost-sharing contract where the supplier shares the retailer's costs of advertising can encourage the retailer to increase the level of advertising investment, which is conducive to improving goodwill and demand for products, so as to achieve profit improvement. From the perspective of retailers, the implementation of advertising marketing strategies can improve the goodwill towards agri-products, further stimulate consumers' demand for high-quality agri-products, and achieve an increase in the sales of high-quality and high-priced agri-products. At the same time, agri-products with high eco-quality bring consumers a higher perception of quality, thus completing a virtuous cycle of goodwill and demand improvement. Furthermore, the supplier would choose to continue to increase the eco-quality investment, and share part of the advertising cost.

### *7.3. Limitation and Future Research Directions*

This paper focuses on the analysis of selling price, eco-quality investment effort and advertising effort in a continuous agri-product supply chain, considering consumers' perception of eco-quality. However, the paper ignores the impact of government subsidy policies on the dynamic strategies of the supply chain. Furthermore, the equilibrium considering the government intervention might be an interesting direction in the future. In addition, although the proposed coordination contract can achieve a Pareto improvement in the supply chain, it does not make the agri-product supply chain achieve perfect coordination. Therefore, it is also meaningful to design a coordination contract to achieve the perfect coordination of the supply chain.

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## Appendix A.

*Appendix A.1. Proof of Proposition 1*

According to the optimal control method, the optimal value functions of the long-term profits of the supplier and the retailer at the time of $t$ are:

$$J_m^D(E,\Theta,G) = e^{-\rho t}V_m^D(E,\Theta,G) \tag{A1}$$

$$J_r^D(E,\Theta,G) = e^{-\rho t}V_r^D(E,\Theta,G) \tag{A2}$$

$V_m^D$ and $V_r^D$ satisfy the Hamilton–Jacobi–Bellman equation for any $E \geq 0, \Theta \geq 0$ and $G \geq 0$.

$$\rho V_m^D(E,\Theta,G) = \max\begin{pmatrix} wD - C_m + V_{mE}^{D'}(\varepsilon I - \delta E) \\ +V_{m\Theta}^{D'}(\theta E - \tau\Theta) + V_{mG}^{D'}(\alpha A + \beta\Theta - \xi G) \end{pmatrix} \tag{A3}$$

$$\rho V_r^D(E,\Theta,G) = \max\begin{pmatrix} (p-w)D - C_r + V_{rE}^{D'}(\varepsilon I - \delta E) \\ +V_{r\Theta}^{D'}(\theta E - \tau\Theta) + V_{rG}^{D'}(\alpha A + \beta\Theta - \xi G) \end{pmatrix} \tag{A4}$$

Take the first partial derivative of the right side of (A3) and (A4) with respect to $p$ and $A$ and make it equal to 0 to obtain $p^D = \frac{a+bw^D}{2b}$, $A^D = \frac{\alpha V_{rG}^{D'}}{K_r}$. Substitute this into Equation (A3), with Equation (A4) on the right-hand side, and find the first-order partial derivatives of $w$ and $I$, and make them equal to 0 to obtain $w^D = \frac{a}{2b}$, $I^D = \frac{\varepsilon V_{mE}^{D'}}{K_m}$. Substitute this into Equation (A3) with Equation (A4), which is then organized to give:

$$\begin{aligned}\rho V_m^D(E,\Theta,G) =& (\theta V_{m\Theta}^{D'} - \delta V_{mE}^{D'})E \\ &+(\beta V_{mG}^{D'} - \tau V_{m\Theta}^{D'})\Theta + (\frac{\gamma a^2}{8b} - \xi V_{mG}^{D'})G + \frac{\varepsilon^2 (V_{mE}^{D'})^2}{2K_m} + \frac{\alpha^2 V_{rG}^{D'} V_{mG}^{D'}}{K_r}\end{aligned} \tag{A5}$$

$$\begin{aligned}\rho V_r^D(E,\Theta,G) &= (\theta V_{r\Theta}^{D'} - \delta V_{rE}^{D'})E \\ &+(\beta V_{rG}^{D'} - \tau V_{r\Theta}^{D'})\Theta + (\frac{a^2\gamma}{16b} - \xi V_{rG}^{D'})G + \frac{\varepsilon^2 V_{rE}^{D'} V_{mE}^{D'}}{K_m} + \frac{\alpha^2 (V_{rG}^{D'})^2}{2K_r}\end{aligned} \tag{A6}$$

By observing the structure of Equations (A5) and (A6), we can see that $V_m^D(E,\Theta,G)$ and $V_r^D(E,\Theta,G)$ are the first-order linear functions of $E$, $\Theta$ and $G$. Thus, the linear expressions for constructing $V_m^D(E,\Theta,G)$ and $V_r^D(E,\Theta,G)$ are:

$$\begin{cases} V_m^D(E,\Theta,G) = m_1E + m_2\Theta + m_3G + m_4 \\ V_r^D(E,\Theta,G) = r_1E + r_2\Theta + r_3G + r_4 \end{cases} \tag{A7}$$

where $m_1, m_2, m_3, m_4, r_1, r_2, r_3, r_4$ are unknown constants, and substituting (A7) into (A5) and (A6), and using the method of coefficients to be determined, we get: $m_1^* = 2\beta\theta K_1 L_1$, $m_2^* = 2\beta K_1 L_2$, $m_3^* = 2K_1L_3$, $m_4^* = \frac{2\beta^2\theta^2\varepsilon^2K_1^2L_1^2}{\rho K_m} + \frac{2\alpha^2K_1^2L_3^2}{\rho K_r}$, $r_1^* = \beta\theta K_1 L_1$, $r_2^* = \beta K_1 L_2$, $r_3^* = K_1L_3$, $r_4^* = \frac{2\beta^2\theta^2\varepsilon^2K_1^2L_1^2}{\rho K_m} + \frac{\alpha^2K_1^2L_3^2}{2\rho K_r}$. Substituting it into $p^D$, $A^D$, $w^D$ and $I^D$, the optimal equilibrium policy under a decentralized decision scenario can be obtained. Substituting the optimal strategy into the state Equations (1)–(3), the optimal trajectories of the product's eco-quality, consumers' eco-perception and product goodwill are obtained. Proposition 2 and 3 can be proved in the same way.

where $L_1 = \frac{1}{16b(\xi+\rho)(\tau+\rho)(\delta+\rho)}$, $L_2 = \frac{1}{16b(\xi+\rho)(\tau+\rho)}$, $L_3 = \frac{1}{16b(\xi+\rho)}$, $K_1 = \gamma\alpha^2$, $H_1 = \Theta_0 - \Theta_\infty^D - \frac{\theta(E_0-E_\infty^D)}{\tau-\delta}$, $H_2 = G_0 - G_\infty^D - \frac{\theta\beta(E_0-E_\infty^D)}{(\tau-\delta)(\xi-\delta)} - \frac{\beta H_1}{\xi-\tau}$, $H_3 = \Theta_0 - \Theta_\infty^C - \frac{\theta(E_0-E_\infty^C)}{\tau-\delta}$, $H_4 = G_0 - G_\infty^C - \frac{\theta\beta(E_0-E_\infty^C)}{(\tau-\delta)(\xi-\delta)} - \frac{\beta H_3}{\xi-\tau}$, $H_5 = \Theta_0 - \Theta_\infty^S - \frac{\theta(E_0-E_\infty^S)}{\tau-\delta}$, $H_6 = G_0 - G_\infty^C - \frac{\theta\beta(E_0-E_\infty^C)}{(\tau-\delta)(\xi-\delta)} - \frac{\beta H_5}{\xi-\tau}$.

*Appendix A.2. Proof of Proposition 4*

(1) The equilibrium solution obtained from Proposition 1, Proposition 2 and Proposition 3 gives the difference in selling price between the centralized and decentralized conditions $p^{C*} - p^{D*} = \frac{-a}{4b} < 0$, and the difference in selling price between the cost-sharing contract and the decentralized condition $p^{S*} - p^{D*} = 0$, so $p^{C*} < p^{D*} = p^{S*}$. In the same way: $I^{C*} > I^{D*} = I^{S*}$, $A^{C*} > A^{S*} > A^{D*}$.

(2) From the equilibrium solution of Proposition 1, Proposition 2 and Proposition 3, we have: the stability value difference of eco-quality under centralized and decentralized conditions $E^C_\infty - E^D_\infty = \frac{2\beta\theta\varepsilon^2 K_1 L_1}{\delta K_m} > 0$, and the difference between the eco-quality stability value under the cost-sharing contract and decentralized conditions $E^S_\infty - E^D_\infty = 0$, so $E^C_\infty > E^D_\infty = E^S_\infty$. Similarly: $\Theta^C_\infty > \Theta^D_\infty = \Theta^S_\infty$ and $G^C_\infty > G^S_\infty > G^D_\infty$.

(3) The equilibrium solution obtained from Proposition 1, Proposition 2 and Proposition 3 yields the difference between the retailer's profit under the cost-sharing contract where the dispersion condition is $J^{S*}_m - J^{D*}_m = \frac{9\alpha^2 K_1^2 L_3^2}{8\rho K_r} > 0$, so $J^{S*}_m > J^{D*}_m$. Similarly: $J^{S*}_r > J^{D*}_r$ and $J^{C*}_s > J^{S*}_s > J^{D*}_s$.

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