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Quality Improvement through Contract Design and Competition in Agricultural Suppply Chains

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Abstract. Quality emerges as a pivotal competitive factor for agricultural products. Recently, retailers within agricultural supply chains have begun investing in technologies to improve quality and designing contracts to incentivize farmers to enhance their labor inputs. The farmers and the retailers incur different quality investment costs, with this cost increasing in the quality they provide. Simultaneously, retailers have embraced the farmer-competition strategy, employing competition to stimulate improved agricultural product quality among farmers. We construct a Stackelberg game model to analyze how farmers' quality investment, retailer's contract design, and profits are affected by the retailer's farmer-competition strategy. We show that the farmer competition introduced by the retailer is not always effective in improving the farmer's quality investment. Similarly, the competition cannot always lead to additional profits for the retailer. Moreover, the supply chain profit suffers from the retailer's farmer-competition strategy when the competition intensity between farmers is relatively large. Our results offer insights for retailers by identifying how should the retailer design the contract to improve the farmer's quality effort given the existence of the farmer competition and under what conditions the retailer should adopt the farmer-competition strategy.

Keywords: Quality management, farmer competition, agricultural supply chain, contract farming

1. Introduction

Quality stands out as a crucial competitive aspect for agricultural products, and quality management holds significant importance within the field of operations management. Large companies, on the one hand, engage in breeding, crop cultivation management, and agricultural technological innovation to enhance quality. For instance, companies may conduct research and development on scientific crop management techniques, including proper procedures of fertilization, irrigation, and pest control. Meanwhile, companies provide contracts including incentive mechanisms to encourage farmers to contribute their labor (Bold et al. 2017). To be specific, farmers can effectively input labor during the planting stage, including regular watering, fertilization, weed control, and pest and disease prevention. These labor activities contribute to maintaining a favorable product growth environment, ultimately enhancing the quality of agricultural products. Therefore, companies pay a quality-based wholesale price to farmers. The higher the product quality, the higher the wholesale price for the farmer.

The method of jointly investing in quality by both companies and farmers is a common practice. For example, Wens, a prominent poultry and livestock farming enterprise in China, distinguishes itself by incorporating advanced technologies in animal breeding, poultry breeding, and feed nutrition. Following investments in these technologies, the company delivers high-quality piglets, chicks, and agricultural inputs to farmers (Wens 2020). Acknowledging the labor-intensive responsibilities shouldered by farmers during the maturation phase, Wens employs a quality-based wholesale price to incentivize farmers' commitment to quality. While the quality-cocreation method and the design of incentives offer a mechanism to motivate farmers' quality investments, the intricacies of delicate seedlings and sophisticated planting/raising methods present additional challenges to farmers, potentially resulting in a decline in product quality.

To address the above issue, the company introduces competition among farmers (Singh 2009). Supplier competition has been widely adopted in traditional manufacturing supply chains. For instance, industry leaders like Toyota and Cisco deliberately maintain multiple suppliers within their networks, allowing them to choose suppliers with lower production costs (Chopra and Sodhi 2004). Besides choosing a supplier based on cost, manufacturers also choose a supplier based on the quality. Electronics manufacturers such as Sun Microsystems employ a scorecard system to allocate demand among suppliers, rewarding those offering higher service quality with increased demand allocation (Cachon and Zhang 2007, Farlow et al. 1996). In a similar context of agricultural supply chains, the varied levels of cost coefficient in quality among farmers contribute to differing degrees of competitive intensity. As a result, product quality may vary among different farmers. Consequently, companies can utilize farmer competition to evaluate the quality performance of different farmers, facilitating the identification of the farmer exhibiting the highest product quality. However, we observe that some companies have not adopted the strategy of farmer competition.

Therefore, this work jointly analyzes the efficacy of the retailer's farmer-competition strategy in influencing the farmer's quality decisions and the retailer's contract design in the agriculture supply chain. Particularly in practice, when the retailer signs the contract with the farmer, he needs to select farmers from hundreds of them located in the same area in one period. Higher competition intensity among farmers (characterized by the relative quality improvement cost) may lead to higher product quality. If the cost advantage of a farmer is relatively high, the quality investment decision of this farmer may not be affected by the competition. Then, the retailer can manipulate the farmers' quality investment decision by the contract design. However, it remains unclear how the farmer's investment in quality evolves following the retailer's introduction of competition among farmers. Moreover, what is the optimal approach for the retailer in designing contracts when engaging with multiple farmers? Does the retailer consistently favor the farmer-competition strategy? Furthermore, what impact does the retailer's adoption of the farmer-competition strategy have on the overall profit of the supply chain?

To answer these questions, we construct a game-theoretical model with the retailer and the farmer co-creating the product quality and the retailer offering a contract containing quality-based wholesale price to two cost-asymmetric farmers. Within this contract, the retailer supplies the farmers with seedlings of a predetermined quality, decided upon by the retailer before the planting stage, and establishes the marginal wholesale price. Subsequently, the farmers determine the quality after entering into a contract with the retailer. In the selling stage, the retailer chooses the farmer with the highest produce quality, pays the wholesale price, and proceeds to sell the products at the retail price. Both the retail and wholesale prices are contingent on the quality, providing incentives for both the retailer and the farmer to enhance the quality. We comprehensively delineate the optimal decisions and contract design under conditions of farmer competition, subsequently comparing our findings with a benchmark case where the retailer exclusively contracts with a single farmer. The following outlines our main findings.

Firstly, the retailer's farmer-competition strategy does not consistently prove effective in enhancing the farmer's investment in quality, particularly when the intensity of farmer competition is small, and the retailer offers substantial incentives (a high marginal wholesale price). Secondly, the retailer needs to design the contract carefully. Specifically, to enhance the farmer's quality investment through the farmer-competition strategy, the retailer must enhance his own investment in quality before the planting stage. Thirdly, the retailer's farmer-competition strategy does not always bring additional benefits to the retailer. When the competition intensity is small, the retailer's profit remains the same as in the no-competition case. Fourthly, the supply chain profit suffers from the retailer's farmer-competition strategy when the competition intensity is relatively large. In this scenario, the improvement in quality under competition can only provide limited benefits to the supply chain, which is insufficient to counterbalance losses incurred by the farmers due to competition. In conclusion, if the retailer can ensure cost-effective labor input from farmers through the implementation of a rigorous farmer screening strategy when signing contracts with the farmer, then the retailer may not need to employ the farmer competition strategy.

The remainder of the study is organized as follows. Section 2 reviews the related literature. Section 3 describes the model. We analyze the benchmark case in Section 4 and discuss the competition case in Section 5. Then, we conclude this study in Section 6.

2. Literature Review

This research mainly relates to three streams of literature: supplier competition, sustainable agricultural operations, and quality co-creation along supply chains.

2.1 Supplier Competition

In the field of supplier competition, a stream of literature studies the supply chain base design. Most of them particularly study the buyer's preference for sourcing from single or dual/multiple suppliers (Li and Wan 2017, Deng and Elmaghraby 2005, Benjaafar et al. 2007). This research focuses on single sourcing and closely relates to the other stream of supplier competition literature, which examines how supplier competition affects the mechanism design and the supply chain performance. For example, Cachon and Zhang (2006) illustrate that the late-fee mechanism and lead-time mechanism can effectively minimize the buyer's cost and supply chain cost when the buyer needs to select one from multiple suppliers who have private capacity information. On the other hand, Li and Wan (2017) examine the impact of supplier competition on suppliers' incentives to improve, and they show that competition between suppliers can be positive or negative depending on the information structure. Similar to them, Özer and Raz (2011) also consider the supplier competition from the supplier's perspective. They analyze how the big supplier's pricing strategy is affected by the case where the buyer has a possible contract option with the small supplier. They find that the big supplier benefits when the small supplier keeps its production cost private. Moreover, Jiang and Wang (2010) consider a decentralized assembly system in which the buyer assembles products from multiple suppliers. They illustrate that suppliers' direct competition helps improve system performance and individual firms' performance. They focus on the suppliers' price competition, considering demand uncertainty in the system. Unlike their research, this research mainly focuses on the quality competition between suppliers. Specifically, each supplier competes on quality, and the retailer only sources from the supplier with the highest quality. We also consider the quality cocreation along the supply chain and aim to understand how the suppliers' competition affects both suppliers' and retailers' quality decisions.

2.2 Sustainable Agricultural Operations

In the agricultural supply chain, deliberate adulteration by farmers threatens public health. Motivated by this, some researchers investigate factors that deter farmers from adulteration. For example, Mu et al. (2016) find that competition is either effective or ineffective in deterring adulteration, depending on the testing mechanism. Levi et al. (2020) illustrate that quality uncertainty, supply chain dispersion, traceability, and testing sensitivity can jointly affect farmer's adulteration behavior. Mu et al. (2014) examine two incentives, confessor rewards, and quality rewards, and two testing methods: pre-mixed individual testing and post-mixed individual testing. They find that quality rewards and pre-mixed individual testing can be harmful to product quality. Additionally, most farmers in the agricultural supply chain are always smallholders and belong to the low-income segment of society. Hence, some research focuses on improving farmers' welfare. For instance, Chen and Tang (2015), Tang et al. (2015) explore the value of information on the farmer. Specifically, they consider different information types, such as private and public information, agricultural advice, forecast information about market demand, etc. Whereas others consider the contact design in the agricultural supply chain. In particular, this stream of literature examines how different types of contracts create value for supply chain performance. Tang et al. (2016) show that a partially-guaranteed-price contract can generate mutual benefits for both the firm and the farmer. Niu et al. (2016) illustrate that the cost-sharing contract can result in a win-win outcome for the farmer and the downstream firm. Ayvaz-Çavdaroğlu et al. (2021) propose two payment policies, a revenue-sharing payment policy and a two-part tariff contract, to incentivize farmers' quality efforts; they find that both policies can coordinate farmers' quality input with the system. Chen and Chen (2021) illustrate that introducing production-management and resource-providing contracts for high-value agricultural products can create value for all contract and non-contract farmers. de Zegher et al. (2019) consider two sourcing channels between the buyer and the farmer, a commodity-based channel and a direct-sourcing channel, and they find that direct-sourcing is not always sufficient to create shared value for supply chain members. Hsu et al. (2019) examine a partnership model between the farmer and the retailer, where the dairy animals are raised by individual farmers during the maturing stage and then by the enterprise during the milking stage. They show that the partnership model is preferred when the enterprise's market size is intermediate. Qian and Olsen (2022) study a contract offered by the buyer in which the buyer specifies a quality standard and offers a multistage payment scheme. Farmers can exert quality-related effort and also show preference toward prompt payment timing. Different from this stream of literature, we consider an innovative contract adopted in the breeding industry, where both the retailer and the farmer are responsible for the quality, with the former investing in technology and the latter investing in labor. Moreover, our model mainly focuses on the pricing and quality strategy from the retailer's point of view, where the retailer in the breeding industry is a monopolist. The retailer provides contracts to multiple farmers who need to compete in quality.

2.3 Quality Co-creation along Supply Chains

Product quality can be divided into two aspects: conformance quality and performance (design) quality (Karaer et al. 2017). Conformance quality focuses on the degree to which a product or service adheres to specified standards, requirements, or specifications. It is primarily concerned with whether a product meets the established criteria and standards, ensuring it is free from defects and conforms to the predetermined specifications. Inspection and adherence to standards play a crucial role in assessing conformance quality. On the other hand, performance quality emphasizes how well a product or service performs its intended functions and meets customer expectations. Rather than focusing on adherence to standards, performance quality evaluates the effectiveness, efficiency, and overall functionality of a product or service in real-world scenarios. Customer satisfaction, reliability, durability, and functionality are key indicators of performance quality. In summary, conformance quality ensures that a product meets established standards, while performance quality assesses how well the product or service performs in terms of functionality and customer satisfaction. Both aspects are crucial for delivering high-quality products and services that meet specifications and meet or exceed customer expectations in practical usage.

In the literature on quality co-creation along supply chains, some researchers study the buyer and supplier's effort to improve conformance quality (Chao et al. 2009, Balachandran and Radhakrishnan 2005, Dong et al. 2016, Zhu et al. 2007), while our study is more related to the literature focusing the performance quality. For instance, Avinadav et al. (2020) study a supply chain in which product quality is co-created by the platform and its service provider, who owns private quality and market information. They focus on the contract design to achieve optimal quality under information asymmetry. Additionally, Mandal et al. (2021) examine whether the retailer's and the supplier's quality efforts are affected by price timing, upfront pricing, and postponed pricing. Unlike theirs, this study mainly focuses on the impact of supplier competition on product quality. Moreover, El Ouardighi and Kogan (2013) consider both quality measures, performance, and conformance quality. They investigate how the supply chain parties allocate effort between these two quality measures. Different from theirs, we mainly study how the performance quality is affected.

3. Model

We consider a monopoly agriculture system with one brand-name retailer (he) sourcing from two potential farmers (she) and selling products to quality-conscious consumers. The retailer and the farmers are engaged in a Stackelberg game. The retailer invests in breeding and agricultural inputs and then offers a quality-based wholesale price contract to farmers. Given the retailer's quality investment decision and contract, the farmers exert quality efforts, produce the product at the planting stage, and sell the mature products directly to the retailer at the farmer's location at the selling season.

Product quality, as perceived by customers, depends on the quality efforts of the retailer (the supply chain leader) and farmers (the supply chain follower). The quality invested by the retailer and the farmers is denoted by θ_r and θ_f, respectively, with the subscript r and f denoting the parameters and variables of the retailer and farmers, respectively. We assume that the cost coefficient of quality investment is not only different between the retailer and the farmers but also between the two competitive farmers. The cost coefficient of improving quality for the retailer, farmer 1, and farmer 2 are denoted by γ_r, γ_f, and $\bar{\gamma}_f$, respectively. In practice, the retailer exerts quality efforts related to technical innovations such as breeding, fertilizer selection, and improvement of planting methods. The farmers exert quality efforts that are related to the labor input. For example, the farmers' diligence in labor-intensive work such as irrigation and fertilization will also improve the quality of the agricultural products. Our model allows for the quality improvement cost through technology investment to be more challenging and expensive than through labor input, i.e., $\gamma_r > \gamma_f$. On the other hand, our model allows asymmetric marginal quality investment costs between the farmers for the capacity utilization level on labor varies among the farmers. To focus on the effect of competition on farmer 1's quality decision, we assume that farmer 2 has a higher cost coefficient of quality than farmer 1, that is $\bar{\gamma}_f > \gamma_f$. There is a positive, convex cost of providing these qualities, denoted by $C_i(\theta_i) = \frac{1}{2}\gamma_i\theta_i^2, i \in \{r, f\}$. The output quality is assumed as a simple additive of these two qualities, that is, $\theta = \theta_r + \theta_f$, and this quality form can be widely found in the literature (Hsu et al. 2019). If either party delivers lower quality, it will impact the overall quality of the agricultural products.

The amount of product a farmer produces is normalized to one. Our model mainly focuses on quality decisions along the supply chain, so we consider an exogenous production quantity. On the other hand, the farmer, who usually has limited resources and land, cannot easily alter the planting/raising quantity. For one unit of product, the product yield is denoted as μ. While real-world situations often encompass yield uncertainties, we consider a fixed yield for traceability.

In the retail market, quality-conscious consumers are willing to pay higher prices for agricultural products with higher performance quality, which motivates the retailer to improve the quality along the supply chain. Hence, we consider the unit-wholesale price and the unit-retail price are linear increasing functions of the final quality θ. Let $w = w_m\theta$, and $p = p_m\theta$. This assumption can be found in the literature (Mu et al. 2016, Hsu et al. 2019). Additionally, in practice, agricultural products are classified into various quality grades based on their performance quality, with the selling price of those products increasing as the grade level rises. For instance, apples are graded into Grade 1, Grade 2, and Premium Grade based on their size, color, and other attributes with the wholesale price of Grade 1 being the lowest and the prices for other levels increasing sequentially according to their respective grades [1]. International Livestock Research Institute also adopts quality-based linear pricing methods for milk, with quality serving as an assessment of the various nutrients in the milk (Draaiyer et al. 2009). The notations used in the analysis are summarized in Table 1.

To explore the effect of upstream competition, we start with a benchmark case (single farmer) in Section 4, then consider the competition case (two farmers) in Section 5.

4. Benchmark Case: Single Farmer

In this case, we consider the retailer only sources from a single farmer and purchases the farmer's product with quality θ. We use superscript B to denote this case. The decision sequence for a single farmer is as follows:

1, The retailer initially invests in quality (θ_r^B) before the planting stage, then decides the marginal wholesale price w_m^B and signs the contract with the farmer.

2, During the planting stage, the farmer exerts efforts and decides her quality (θ_f^B).

3, The retailer sources from the farmer with the wholesale price $w^B = w_m^B\theta^B = w_r^B(\theta_r^B + \theta_f^B)$ at the selling season and then sells his products to the retail market at the retail price $p^B = p_m^B\theta^B = p_m^B(\theta_r^B + \theta_f^B)$.

The farmer's profit maximization problem can be formulated as follows:

$$\Pi_f^B = \max_{\theta_f^B \geq 0} \left\{ \mu w_m^B \theta^B - \frac{1}{2}\gamma_f \theta_f^{B2} \right\} \tag{1}$$

We can easily show that the farmer's profit is concave in θ_f^B and then we can get

Table 1 Notations

Variable	Definition
μ	Product yield
w	Wholesale price
w_m	Marginal wholesale price
p	Retail price
p_m	Customer's marginal value of quality
θ	Product quality
θ_f	The quality invested by the farmers
θ_r	The quality invested by the retailer
γ_f	Farmer 1's cost coefficient for quality
$\bar{\gamma}_f$	Farmer 2's cost coefficient for quality
γ_r	Retailer's cost coefficient for quality

the farmer's optimal quality in the following Lemma.

Lemma 1 *In the benchmark case, the farmer's optimal quality is given by* $\theta_f^B = \frac{w_m^B \mu}{\gamma_f}$.

Lemma 1 shows that the farmer's optimal quality increases with the yield and marginal wholesale price and decreases with her cost coefficient of quality. Additionally, the retailer's profit maximization problem can be written as follows:

$$\Pi_r^B = \max_{\theta_r^B, w_m^B \geq 0} \left\{ \mu \left(p_m - w_m^B \right) \theta^B - \frac{1}{2} \gamma_r \theta_r^{B2} \right\} \tag{2}$$

Solving the profit maximization problem of the retailer, we can get his optimal decisions, which are illustrated in the following Lemma.

Lemma 2 *In the benchmark case, the farmer's optimal quality, the retailer's optimal quality, and the optimal marginal wholesale price in the equilibrium are given by* $\theta_f^{B*} = \frac{w_m^{B*} \mu}{\gamma_f}$, $\theta_r^{B*} = \frac{p_m \mu}{2\gamma_r - \gamma_f}$, $w_m^{B*} = \frac{p_m(\gamma_r - \gamma_f)}{2\gamma_r - \gamma_f}$, *respectively.*

The marginal wholesale price and the retailer's quality increase as the customer's value of quality increases, suggesting that the retailer enhances the quality and increases the marginal wholesale price, thereby incentivizing the farm's quality. Furthermore, if the retailer's cost coefficient of quality increases, the retailer will increase the marginal wholesale price to incentivize the farmer's quality and, at the same time, decrease his investment in quality. If the farmer's cost coefficient of quality increases, the retailer will decrease the marginal wholesale price to reduce the cost paid to the farmer and increase his investment in quality. These dynamics illustrate that the retailer, acting as the Stackelberg leader, possesses the ability to allocate resources considering the cost coefficients associated with different quality types. Therefore, the design of the contracts is crucial to the retailer.

Then we substitute the farmer's and retailer's optimal decisions into the quality and the players' profit, respectively, we can get the equilibrium quality and profit. To be specific, the equilibrium quality is $\theta^{B*} = \frac{p_m \gamma_r \mu}{2\gamma_r \gamma_f - \gamma_f^2}$. The equilibrium profits of the farmer and the retailer are $\pi_f^{B*} = \frac{p_m^2 \mu^2 (\gamma_r - \gamma_f)(\gamma_r + \gamma_f)}{2\gamma_f (2\gamma_r - \gamma_f)^2}$, and $\pi_r^{B*} =$

$\frac{p_m^2\mu^2\gamma_r}{2\left(2\gamma_r\gamma_f-\gamma_f^2\right)}$, respectively.

5. Farmer Competition

In this section, our objective is to comprehend the impact of competition introduced by the retailer on product quality and profitability. We initially explore how the presence of competition, represented by an additional farmer, influences the quality decisions made by the incumbent farmer. Subsequently, we examine how this influences the retailer's contract design. Particularly, we derive the equilibrium contract design for the retailer in the competitive scenario. Finally, we conduct a comparative analysis of the supply chain profit between the benchmark case and the farmer competition case to discern the effects of the retailer's farmer-competition strategy.

The model is similar to the benchmark model, except with the retailer considering sourcing from two farmers, farmer 1 and farmer 2, who have asymmetric cost coefficients. Farmer 1 is the incumbent farmer existing in the benchmark case, whose cost coefficient of quality is γ_f, while farmer 2 is the additional farmer. To focus on the effect of competition on farmer 1's quality decision, we assume that farmer 2 has a higher cost coefficient of quality than farmer 1, that is, $\bar{\gamma}_f > \gamma_f$. In the following, we will use overline to denote parameters, decisions, and profits related to farmer 2.

Specifically, as the supply chain leader, the retailer decides his quality co-created level and provides quality-based wholesale price to both farmers before the planting stage. We need to note that as the retailer raises quality by delivering innovative techniques, the additional cost the retailer incurs in providing quality cocreated contracts to more farmers is negligible. Then he sources from the farmer whose product quality is higher. The farmer whom the retailer does not select earns zero profit. Here, we also assume that the retailer prefers to source from farmer 1 whenever these farmers' quality is indifferent. The competition model, in this case, follows the definition of supplier-selection based on the research of Karaer et al. (2017), Benjaafar et al. (2007) and Jiang and Wang (2010). Additionally, the superscript C represents the competition model, and the sequence of events in this section is as follows.

1, The retailer initially invests in quality (θ_r^C) before the planting stage, then decides the marginal wholesale price w_m^C, and signs the contract with farmers.

2, Farmer 1 and farmer 2 compete in a static game of complete information, and they simultaneously decide their quality, θ_f^C and $\bar{\theta}_f^C$, respectively. After observing the products' quality at the selling season, the retailer then sources from the farmer with the highest quality level ($\max(\theta_f^C, \bar{\theta}_f^C)$). The winning farmer earns the retailer's entire business and incurs a related cost. However, the farmer who does not win the competition earns zero profit.

3, The retailer sells his products at the retail market.

The farmers' profit can be formulated as follows:

$$\Pi_f^C = \mu w_m^C \theta^C - \frac{1}{2}\gamma_f \theta_f^{C2}$$

$$\bar{\Pi}_f^C = \mu w_m^C \bar{\theta}^C - \frac{1}{2}\bar{\gamma}_f \bar{\theta}_f^{C2}$$

In our model, farmer 1 has a lower cost coefficient of investing in quality, so she always earns the retailer's business. Since we focus on how the existence of competition affects farmer 1's quality decision, we demonstrate farmer 1's profit maximization problem as follows:

$$\Pi_f^C = \max_{\theta_f^C \geq 0} \left\{ \mu w_m^C \theta^C - \frac{1}{2}\gamma_f \theta_f^{C2} \right\} \tag{3}$$
$$\text{s.t.} \quad \theta^C > \bar{\theta}^C$$

where the constraint represents that farmer 1 needs to ensure her output quality is larger than that of farmer 2. Farmer 2, whose cost coefficient of investing in quality is larger, will strive to invest in quality and choose a maximum quality she can achieve that makes her profit equal to zero. Hence, farmer 2's quality is

$$\theta_f^{CM} = \frac{w_m^C \mu + \sqrt{2\bar{\gamma}_f w_m^C \theta_r^C \mu + w_m^{C2} \mu^2}}{\bar{\gamma}_f}$$

(referred to as the maximum quality of farmer 2 hereafter, and represented by superscript CM) and $\bar{\Pi}_f^C\left(\theta_{\mathrm{f}}^{CM}\right) = 0$. Additionally, recall that if the competition does not exist, farmer 1 chooses the profit-maximizing quality

$$\theta_f^{CO} = \frac{w_m^C \mu}{\gamma_f}$$

(shown in Lemma 1, represented by superscript CO). The following Proposition demonstrates how the farmers' quality decisions are affected by the retailer's decisions in the contract.

Proposition 1 $\frac{\partial \theta_{\mathrm{f}}^{CO}}{\partial w_m^C} > 0$, $\frac{\partial \theta_{\mathrm{f}}^{CM}}{\partial w_m^C} > 0$, $\frac{\partial \theta_{\mathrm{f}}^{CM}}{\partial \theta_r^C} > 0$.

Proposition 1 reveals that the profit-maximizing quality for farmer 1 increases with the marginal wholesale price. In contrast, the maximum quality of farmer 2 rises with both the retailer's marginal wholesale price and the retailer's quality. Proposition 1 first implies that a higher marginal wholesale price can offer stronger incentives to the farmer, consequently increasing the farmer's quality investment. Additionally, farmer 2, aiming to prevail in the competition, is compelled to invest in quality as much as possible until the quality cost becomes prohibitively high, resulting in her profit reaching zero. As a result, given that her revenue rises with both the retailer's marginal wholesale price and the retailer's quality, she will allocate all revenue to quality investment. Therefore, θ_{f}^{CM} not only increases with the marginal wholesale price but also increases with the retailer's quality.

With the existence of competition, farmer 1 is constrained to provide the product with higher quality; otherwise, the retailer will not source from her. Therefore, farmer 1's decision of quality becomes $\theta_f^C = \max(\theta_f^{CM}, \theta_f^{CO})$. If $\theta_f^{CM} \geq \theta_f^{CO}$, competition improves farmer 1's quality investment from θ_f^{CO} to θ_f^{CM}; otherwise, if $\theta_f^{CM} < \theta_f^{CO}$, then competition does not affect farmer 1's quality decision. The following proposition discusses how the farmer competition introduced by the retailer affects farmer 1's quality decision and the related retailer's contract design.

Proposition 2 *(i) When the competition intensity is small, that is, $0 < \gamma_f \leq \frac{\bar{\gamma}_f}{2}$, we consider the following two cases:*

(i-a) If $w_m^C > \frac{2\gamma_f{}^2\theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu}$, then $\theta_f^{CO} > \theta_f^{CM}$.

(i-b) If $0 < w_m^C \leq \frac{2\gamma_f{}^2\theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu}$, then $\theta_f^{CO} \leq \theta_f^{CM}$.

(ii) When the competition intensity is large, that is, $\frac{\bar{\gamma}_f}{2} < \gamma_f < \bar{\gamma}_f$, $\theta_f^{CO} < \theta_f^{CM}$.

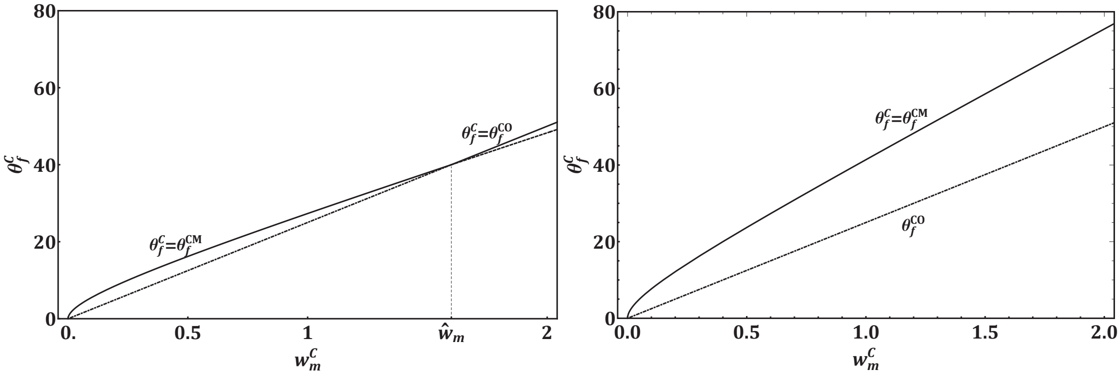
Proposition 2 illustrates that the effectiveness of competition in enhancing farmer 1's quality is collectively influenced by the competition intensity and the contract designed by the retailer. First, the competition does not take into effect in improving farmer 1's quality when farmer 1 holds a substantial cost advantage in quality investment (the competition intensity is small), and the retailer's marginal wholesale price is relatively high, that is, $\theta_f^C = \theta_f^{CO}$ when $0 < \gamma_f \leq \frac{\bar{\gamma}_f}{2}$ and $w_m^C > \frac{2\gamma_f{}^2\theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu}$. This is due to the fact that a substantial cost advantage in farmer 1's quality ensures farmer 1's quality superiority and a relatively high marginal wholesale price provides large incentives for farmer 1 to invest in quality. Consequently, even if farmer 2 strives to choose a maximum quality θ_f^{CM}, θ_f^{CM} is still smaller than θ_f^{CO}. Therefore, the competition failed to improve farmer 1's quality in this condition. Secondly, when the competition intensity between farmers is small but the retailer provides a relatively small marginal wholesale price, that is, $0 < \gamma_f \leq \frac{\bar{\gamma}_f}{2}$ and $0 < w_m^C \leq \frac{2\gamma_f{}^2\theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu}$, the competition starts to enhance farmer 1's quality investment from θ_f^{CO} to θ_f^{CM}. In this scenario, lower wholesale price decreases farmer 1's incentive to invest in quality, leading the quality that maximizes farmer 1's profit to be smaller than farmer 2's maximum quality, i.e., $\theta_f^{CO} \leq \theta_f^{CM}$. Hence, competition comes into effect in enhancing farmer 1's quality investment, and farmer 1's optimal quality equals to farmer 2's quality, i.e., $\theta_f^C = \theta_f^{CM}$. Thirdly, when the competition intensity between farmers is large, that is, $\frac{\bar{\gamma}_f}{2} < \gamma_f < \bar{\gamma}_f$, the competition between farmers gets tougher, farmer 1 reacts to the threat of farmer 2's competition by increasing quality investment. To be specific, farmer 1's optimal quality decision is affected by the interaction between the degree of competition and the retailer's wholesale price. Figure 1 illustrates how the marginal wholesale price w_m^C affects the farmer's incentives to invest in quality, consequently influencing farmer 1's quality decisions. In Figure 1, the solid lines represent farmer 1's optimal quality. These results illustrate that when the retailer adopts the farmer-competition strategy, he should design the contract carefully; otherwise, the farmer-competition strategy might be ineffective in motivating farmer's quality investment.

Proposition 2 shows the farmers' best response and illustrates whether the competition and the retailer's contract design are effective in improving farmer 1's quality. However, the farmers' different quality decisions, in turn affect the retailer's contract design. Hence, anticipating the farmer's quality, the retailer decides his quality and marginal wholesale price to maximize his profit, which is

$$\Pi_r^C = \max_{\theta_r^C, w_m^C \geq 0} \mu \left(p_m - w_m^C\right) \max\left(\theta^C, \bar{\theta}^C\right) - \frac{1}{2}\gamma_r \theta_r^{C2} \tag{4}$$

and the retailer's decisions are listed in Lemma 3. Hereafter, we use superscript CO and CM to represent the decisions, parameters and profits when $\theta_f^C = \theta_f^{CO}$ and $\theta_f^C = \theta_f^{CM}$, respectively. The following Lemma illustrates the optimal contract design for the retailer in the competition scenario.

Lemma 3 *(i) Anticipating farmer 1's quality* $\theta_f^C = \theta_f^{CO} = \frac{w_m^C\mu}{\gamma_f}$*, the retailer's quality and marginal wholesale price are* $\theta_r^{CO} = \frac{p_m\mu}{2\gamma_r - \gamma_f}$ *and* $w_m^{CO} = \frac{p_m(\gamma_r - \gamma_f)}{2\gamma_r - \gamma_f}$*. Consequently, the profits of farmer 1*



(a) $0 < \gamma_f \le \frac{\bar{\gamma}_f}{2}$ (b) $\frac{\bar{\gamma}_f}{2} < \gamma_f < \bar{\gamma}_f$

Figure 1 Farmer 1's Optimal Quality with Respect to the Marginal Wholesale Price

Notes. The parameters are $\gamma_f = 0.2$, $\bar{\gamma}_f = 0.5$ (in subplot (a)), $\bar{\gamma}_f = 0.3$ (in subplot (b)), $\mu = 5$, $\theta_r^C = 10$. In subplot (a), $\hat{w}_m^C = \frac{2{\gamma_f}^2\theta_r^C}{(\bar{\gamma}_f-2\gamma_f)\mu}$.

and retailer are $\Pi_r^{CO} = \frac{p_m^2\gamma_r\mu^2}{4\gamma_r\gamma_f-2\gamma_f^2}$ *and* $\Pi_f^{CO} = \frac{p_m^2(\gamma_r-\gamma_f)(\gamma_r+\gamma_f)\mu^2}{2\gamma_f(-2\gamma_r+\gamma_f)^2}$*, respectively.*

(ii) Anticipating farmer 1's quality $\theta_f^C = \theta_{\mathrm{f}}^{CM} = \frac{w_m^C\mu+\sqrt{2\bar{\gamma}_f w_m^C\theta_r^C\mu+w_m^{C2}\mu^2}}{\bar{\gamma}_f}$*, the retailer's quality and marginal wholesale price are* $\theta_r^{CM} = \frac{p_m\mu}{\gamma_r}$ *and* $w_m^{CM} = \frac{p_m\gamma_r}{2(\gamma_r+\bar{\gamma}_f)}$*. Consequently, the profits of farmer 1 and the retailer are* $\Pi_r^{CM} = \frac{p_m^2(\gamma_r+\bar{\gamma}_f)\mu^2}{2\gamma_r\bar{\gamma}_f}$ *and* $\Pi_f^{CM} = \frac{p_m^2(\bar{\gamma}_f-\gamma_f)\mu^2}{2\bar{\gamma}_f^2}$*, respectively.*

As stated in the discussion, the retailer can choose the quality investment and offer a wholesale price to the farmers to induce them to choose a quality improvement level that maximizes his profit under the competition. In Lemma 3 (i), the retailer's contract design remains the same as the benchmark case (Lemma 2), and then the farmer 1 chooses the profit-maximizing quality. On the other hand, if the retailer alters his decisions, where $\theta_r^{CM} = \frac{p_m\mu}{\gamma_r}$ and $w_m^{CM} = \frac{p_m\gamma_r}{2(\gamma_r+\bar{\gamma}_f)}$ (Lemma 3 (ii)), farmer 1 is induced to compete with farmer 2 and improves her quality to θ_f^{CM}.

Then we compare the differences between retailer's decisions. The quality level set by the retailer to induce quality improvement from farmer 1 is higher than the case in which farmer 1's quality investment remains the same as the benchmark case, that is, $\theta_r^{CM} > \theta_r^{CO}$. If farmer 1 is induced to compete with farmer 2 in the market, farmer 1's quality investment is farmer 2's maximum quality, i.e., $\theta_f^C = \theta_{\mathrm{f}}^{CM}$. Hence, the retailer anticipates that his investment in quality will directly improve farmer 1's quality (θ_{f}^{CM}, See Proposition 1), and in turn, he can benefit from the high output quality. In contrast, if farmer 1's quality investment remains the same as the benchmark case, i.e., $\theta_f^C = \theta_{\mathrm{f}}^{CO}$, the quality is independent of the retailer's quality. As a result, the retailer is reluctant to invest in quality if he does not want to introduce competition between farmers. Overall, the retailer can anticipate the farmer's quality and designs the contract that maximizes his profit.

Next, we characterize the retailer's equilibrium quality investment and contract design by comparing the retailer's profit between two scenarios: one where farmer 1 does not have to change her quality investment and another where farmer 1 is compelled to improve the quality. The retailer then selects the marginal wholesale price and quality that result in higher profits for him. The equilibrium decisions of the retailer are illustrated in the following Proposition.

Proposition 3 *In equilibrium, the retailer's optimal quality and marginal wholesale price are*

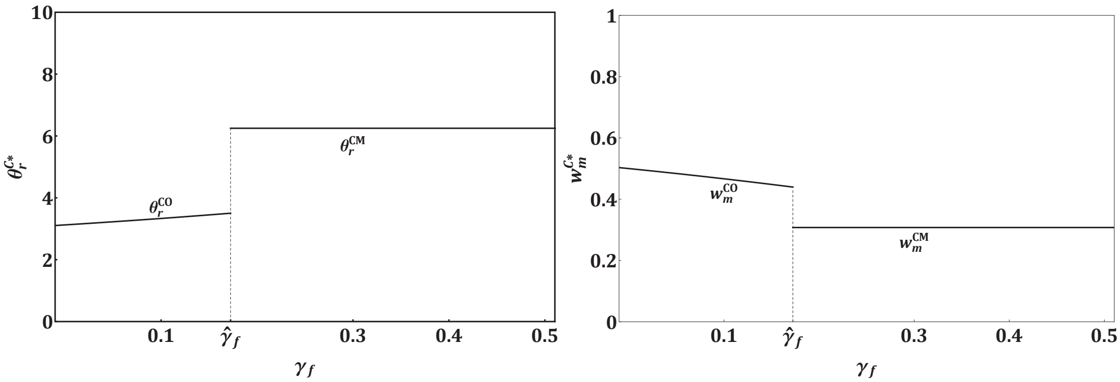
$$\theta_r^{C*}, w_m^{C*} = \begin{cases} \theta_r^{CO}, w_m^{CO}, \\ \quad \text{if} \quad 0 < \gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}} \\ \theta_r^{CM}, w_m^{CM}, \\ \quad \text{if} \quad \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}} < \gamma_f < \bar{\gamma}_f \end{cases} \tag{5}$$

When farmer 1 is competitive in quality investment ($0 < \gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}$), the retailer's optimal quality and marginal wholesale price are θ_r^{CO} and w_m^{CO}. On this occasion, the retailer takes advantage of farmer 1's low cost coefficient and sets a higher marginal wholesale price to encourage farmer 1 to increase quality investment. On the other hand, anticipating that farmer 1's quality is not affected by his quality investment, he invests a relatively low quality level to reduce cost (θ_r^{CO} in Figure 2 (a)) and provides a relatively high marginal wholesale price to incentivize farmer's quality investment (w_m^{CO} in Figure 2 (b)). Additionally, if the competition intensity increases ($\gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}} < \gamma_f < \bar{\gamma}_f$), the retailer's optimal quality and marginal wholesale price become θ_r^{CM} and w_m^{CM}. In this situation, the farmers' competition gets more intense, so the retailer starts to utilize the competition strategy to increase the farmer's quality investment. Specifically, the retailer invests a relatively high quality level to enhance farmer 2's quality investment and simultaneously decreases the marginal wholesale price, compelling farmer 1 to improve the quality investment (θ_r^{CM} and w_m^{CM} in Figure 2 (a) and (b)). It is worth noting that when the competition intensity is small ($0 < \gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}$), introducing competition to the supply side cannot bring additional profit for the retailer. The insight from Proposition 3 is related to the practice. Though some companies in India implement a farmer competition strategy, Wens, the leading company in China, does not adopt it. Specifically, it adopts a rigorous farmer screening strategy when signing contracts with the farmer, making sure that the farmer in the contract is cost-effective. To further explore the effect of the retailer's competition strategy, we compare the equilibrium quality and profits between the benchmark case and the competition case.

Proposition 4 *(i) If competition intensity is small ($0 < \gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}$), then $\theta^{C*} = \theta^{B*}$, $\pi_f^{C*} = \pi_f^{B*}$, $\pi_r^{C*} = \pi_r^{B*}$.*

(ii) If competition intensity is large ($\gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}} < \gamma_f < \bar{\gamma}_f$), then $\theta^{C*} > \theta^{B*}$, $\pi_f^{C*} < \pi_f^{B*}$, $\pi_r^{C*} > \pi_r^{B*}$.

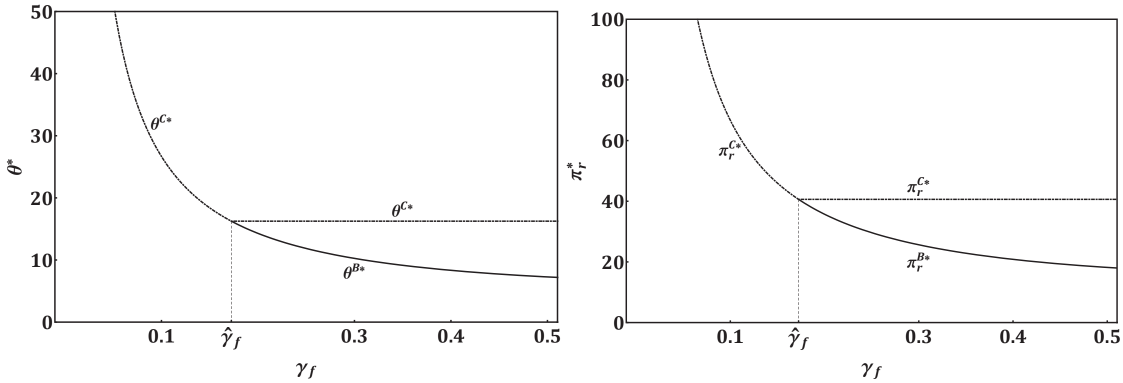
Proposition 4 shows that the retailer's profit is at least equivalent to that in the benchmark case. In instances where the retailer opts to design the contract such that the farmer 1 does not need to change her quality investment ($0 < \gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}$), quality and profits in the competition case are the same as in the benchmark case. Conversely, when the retailer's competition strategy involves forcing competition between farmers ($\gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}} < \gamma_f < \bar{\gamma}_f$), then $\theta^{C*} > \theta^{B*}$, farmer 1 improves quality,



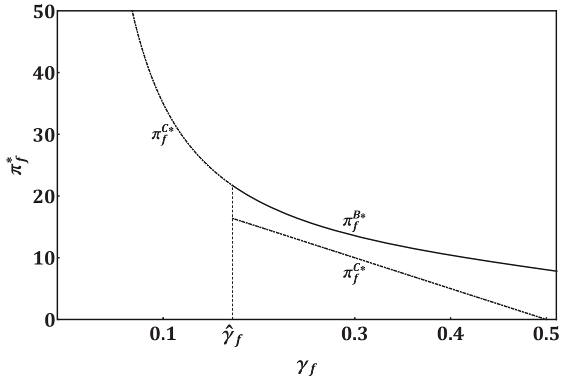
(a) Retailer's Quality (b) Marginal Wholesale Price

Figure 2 Retailer's Equilibrium Decisions in the Competition Case

Notes. The parameters are $\gamma_r = 0.8$, $\bar{\gamma}_f = 0.5$, $p_m = 1$, $\mu = 5$. In Figure 2, $\hat{\gamma}_f = \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}}$.



(a) Product Quality (b) Retailer's Profit



(c) Farmer's Profit

Figure 3 Quality and Profit Comparison between the Benchmark Case and the Competition Case

Notes. The parameters are $\gamma_r = 0.8$, $\bar{\gamma}_f = 0.5$, $p_m = 1$, $\mu = 5$. In Figure 3, $\hat{\gamma}_f = \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}}$.

resulting in increased output quality. Consequently, the retailer benefits from the higher quality, thereby earning more profit. However, it is essential to note that the competition leads to a reduction in farmers' profits, as they are compelled to compete with each other.

Furthermore, we analyze the supply chain's profit in Proposition 5. According to Proposition 5, the supply chain benefits from the retailer's competition strategy when the competition intensity is either small ($\gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}$) or relatively large ($\gamma_f > \max\left(\tilde{\gamma}_f, \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}\right)$), as depicted in Figure 4. Referring back to Proposition 4, the retailer increases the supply chain quality by utilizing a farmer-competition strategy, consequently enhancing the supply chain profit. Conversely, the supply chain profit may be adversely affected by competition when the competition intensity between farmers lies in the medium region ($\gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}} < \gamma_f < \tilde{\gamma}_f$). In such instances, the additional quality improvement from farmers' competition is not sufficient to offset farmer's profit losses due to competition, resulting in a decrease in supply chain profit.

Proposition 5 $\Pi_r^{C*} + \Pi_f^{C*} \ge \Pi_r^{B*} + \Pi_f^{B*}$ *if and only if* $\gamma_f \le \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}$ *and* $\gamma_f > \max\left(\tilde{\gamma}_f, \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}}\right)$*; otherwise,* $\Pi_r^{C*} + \Pi_f^{C*} < \Pi_r^{B*} + \Pi_f^{B*}$ *if and only if* $\gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r+\bar{\gamma}_f}} < \gamma_f < \tilde{\gamma}_f$*, where* $\tilde{\gamma}_f$ *is the solution to* $\Pi_r^{C*} + \Pi_f^{C*} = \Pi_r^{B*} + \Pi_f^{B*}$.

6. Conclusion

In this study, we examine the impact of the retailer's farmer-competition strategy on farmers' optimal quality decisions and the retailer's contract design. Even though prior research has addressed improving product quality through contracts or suppliers' competition, the interaction between farmers' competition and the retailer's contract design in the agricultural supply chain is still unclear. To study this effect, we build a Stackelberg game model where the retailer offers contracts to two farmers and procures from the one with superior produce quality.

Our findings reveal that adopting competition on the farmers' side can increase the farmer's quality except when the competition intensity is low and the retailer offers a high wholesale price to farmers. The retailer can manipulate the farmer's quality investment by increasing his investment in quality improvement and lowering the wholesale price. However, when competition intensity is low, the competitive dynamics do not materialize, resulting in failed quality improvement.

We also find that whether the competition can be an effective strategy to bring additional profit to the retailer depends on the degree of competition. More intense competition leads to higher farmer quality investment. Hence, the retailer's profit is improved. More interestingly, there are many settings where the supply chain profits are reduced even if the farmer-competition strategy improves the quality due to the fact that the farmers lose profit from competition. Consequently, large companies should cautiously

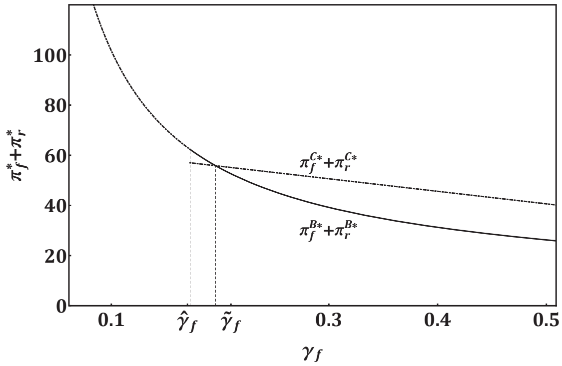


Figure 4 Supply Chain's Profit Comparison between the Benchmark Case and the Competition Case.

Notes. The parameters are $\gamma_r = 0.8$, $\bar{\gamma}_f = 0.5$, $p_m = 1$, $\mu = 5$. In Figure 4, $\hat{\gamma}_f = \gamma_{\mathrm{r}} - \sqrt{\frac{\gamma_{\mathrm{r}}^3}{\gamma_{\mathrm{r}}+\bar{\gamma}_f}}$, $\tilde{\gamma}_f$ is the solution to $\Pi_r^{C*} + \Pi_f^{C*} = \Pi_r^{B*} + \Pi_f^{B*}$.

embrace the farmer-competition strategy, and if they choose to implement this strategy, the contract requires meticulous design. These results provide theoretical instructions for the companies in the agricultural supply chain, particularly when the retailer signs the contract with the farmer, he needs to select farmers from hundreds of them located in the same area.

There are several possible avenues for future research. First, our model assumes that the farmer's quality investment is an addition to the quality improvement of the retailer's quality. Adding a new factor of farmer's ability to deal with high-tech seedlings would allow us to consider situations where the quality might be reduced given the advanced seedlings/planting methods. Second, we also assume that the quality is a variable that can be directly decided by the farmer and the retailer. However, one could consider the uncertainty of quality.

Appendix A Proofs

Proof of Lemma 1. It is easy to show farmer's profit is concave in quality since we have

$$\frac{\mathrm{d}^2\Pi_f^B}{\mathrm{d}\theta_f^{B2}} = -\gamma_f < 0$$

Hence, the farmer's optimal quality satisfying $\frac{\mathrm{d}\Pi_f^B}{\mathrm{d}\theta_f^B} = 0$, that is, $\theta_f^B = \frac{w_m^B \mu}{\gamma_f}$. ■

Proof of Lemma 2. Anticipating farmer's optimal quality, retailer decides the marginal wholesale price w_m^B. Π_r^B is concave in w_m^B since

$$\frac{\partial^2\Pi_r^B}{\partial w_m^{B2}} = -\frac{2\mu^2}{\gamma_f} < 0$$

Hence, the retailer's optimal marginal wholesale price is $w_m^B = \frac{-\gamma_f\theta_r^B + p_m\mu}{2\mu}$ satisfying $\frac{\partial\Pi_r^B}{\partial w_m^B} = 0$

Next, the retailer decides his quality θ_r^B. Similarly, we can show the retailer's profit is concave in θ_r^B since

$$\frac{\partial^2\Pi_r^B}{\partial\theta_r^{B2}} = \frac{-2\gamma_r+\gamma_f}{2} < 0$$

Hence, the retailer's optimal quality is $\theta_r^{B*} = \frac{p_m\mu}{2\gamma_r-\gamma_f}$ satisfying $\frac{\partial\Pi_r^B}{\partial\theta_r^B} = 0$. Plug θ_r^{B*} into the optimal marginal wholesale price, we have $w_m^{B*} = \frac{p_m(\gamma_r-\gamma_f)}{2\gamma_r-\gamma_f}$. ■

Proof of Proposition 1. The first derivative of θ_f^{CO} with respect to w_m^C is

$$\frac{\partial \theta_{\mathrm{f}}^{CO}}{\partial w_m^C} = \frac{\mu}{\gamma_f} > 0$$

Similarly, we can show

$$\frac{\partial \theta_{\mathrm{f}}^{CM}}{\partial w_m^C} = \frac{\mu + \frac{\mu\left(\bar{\gamma}_f \theta_r^C + w_m^C \mu\right)}{\sqrt{\mu w_m^C \left(2\bar{\gamma}_f \theta_r^C + w_m^C \mu\right)}}}{\bar{\gamma}_f} > 0$$

$$\frac{\partial \theta_{\mathrm{f}}^{CM}}{\partial \theta_r^C} = \sqrt{\frac{w_m^C \mu}{2\bar{\gamma}_f \theta_r^C + w_m^C \mu}} > 0$$

■

Proof of Proposition 2. Define

$$G\left(w_m^C\right) = \theta_{\mathrm{f}}^{CM} - \theta_{\mathrm{f}}^{CO}$$

$G\left(w_m^C\right)$ is concave in w_m^C since

$$\frac{\partial^2 G(w_m^C)}{\partial w_m^{C2}} = -\frac{\bar{\gamma}_f \theta_r^{C2} \sqrt{\mu}}{\left(w_m^C (2\bar{\gamma}_f \theta_r^C + w_m^C \mu)\right)^{3/2}} < 0$$

Then solving for $G\left(w_m^C\right) = 0$, we can show that $G\left(w_m^C\right) = 0$ when $w_m^C = 0$ and $w_m^C = \frac{2\gamma_f{}^2 \theta_r^C}{(\bar{\gamma}_f - 2)\mu}$. Then we discuss the value of $\frac{2\gamma_f{}^2 \theta_r^C}{(\bar{\gamma}_f - 2)\mu}$,

(i) If $\frac{2\gamma_f{}^2 \theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu} > 0$, that is, $0 < \gamma_f \leq \frac{\bar{\gamma}_f}{2}$, $G(w_m^C) > 0$ when $0 < w_m^C < \frac{2\gamma_f{}^2 \theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu}$;

(ii) If $\frac{2\gamma_f{}^2 \theta_r^C}{(\bar{\gamma}_f - 2\gamma_f)\mu} < 0$, that is, $\gamma_f > \frac{\bar{\gamma}_f}{2}$, $G\left(w_m^C\right) > 0$ when $w_m^C > 0$. ■

Proof of Lemma 3. (i) The proof of Lemma 3 (i) is the same as the Lemma 2 given the profit function of the retailer and the farmer's quality are the same in these two cases.

(ii) Anticipating farmer's quality $\theta_{\mathrm{f}}^C = \theta_{\mathrm{f}}^{CM} = \frac{w_m^C \mu + \sqrt{2\bar{\gamma}_f w_m^C \theta_r^C \mu + w_m^{C2} \mu^2}}{\bar{\gamma}_f}$, retailer decides the marginal wholesale price w_m^{CM}. Π_r^{CM} is concave in w_m^{CM} since

$$\frac{\partial^2 \Pi_r^{CM}}{\partial w_m^{CM2}} < 0$$

(See Equation (A.1)). In Equation (A.1),

$$T = w_m^{CM} \mu \left(2\bar{\gamma}_f \theta_r^{CM} + w_m^{CM} \mu\right) > 0$$

Hence, the retailer's optimal marginal wholesale price is $w_m^{CM} = \frac{p_m^2 \mu}{2(\bar{\gamma}_f \theta_r^C + p_m \mu)}$ satisfying $\frac{\partial \Pi_r^{CM}}{\partial w_m^{CM}} = 0$.

Next, the retailer decides his quality θ_r^{CM}. Similarly, we can show the retailer's profit is concave in θ_r^{CM} since

$$\frac{\partial^2 \Pi_r^{CM}}{\partial \theta_r^{CM2}} = -\gamma_r < 0$$

Hence, the retailer's optimal quality is $\theta_r^{CM*} = \frac{p_m \mu}{\gamma_r}$ satisfying $\frac{\partial \Pi_r^{CM}}{\partial \theta_r^{CM}} = 0$. Plug θ_r^{CM} into the optimal marginal wholesale price, we have $w_m^{\mathrm{CM*}} = \frac{p_m \gamma_r}{2(\gamma_r + \bar{\gamma}_f)}$. ■

Proof of Proposition 3. Given $\Pi_r^{CO} = \frac{p_m^2 \gamma_r \mu^2}{4\gamma_r \gamma_f - 2\gamma_f^2}$ and $\Pi_r^{CM} = \frac{p_m^2 (\gamma_r + \bar{\gamma}_f) \mu^2}{2\gamma_r \bar{\gamma}_f}$, the platform chooses the higher profit between Π_r^{CO} and Π_r^{CM}. Define

$$\begin{aligned}\hat{\Pi}_r^C &= \Pi_r^{CO} - \Pi_r^{CM} \\ &= \frac{1}{2} p_m^2 \mu^2 \left(-\frac{1}{\gamma_r} - \frac{1}{\bar{\gamma}_f}\right) + \frac{1}{2} p_m^2 \mu^2 \frac{\gamma_r}{2\gamma_r \gamma_f - \gamma_f{}^2}\end{aligned}$$

$\hat{\Pi}_r^C$ is convex in γ_f since

$$\frac{\partial^2 \hat{\Pi}_r^C}{\partial \gamma_f^2} = \frac{p_m^2 \mu^2 \gamma_r \left(4\gamma_r^2 - 6\gamma_r \gamma_f + 3\gamma_f^2\right)}{\left(2\gamma_r - \gamma_f\right)^3 \gamma_f^3} > 0$$

and additionally, $\hat{\Pi}_r^C$ is minimized at $\gamma_f = \gamma_r$. Then solving for $\hat{\Pi}_r^C = 0$, we can show that there exists a $\hat{\gamma}_f = \gamma_{\mathrm{r}} - \sqrt{\frac{\gamma_{\mathrm{r}}^3}{\gamma_{\mathrm{r}} + \bar{\gamma}_f}} < \gamma_{\mathrm{r}}$ such that $\hat{\Pi}_r^C\left(\hat{\gamma}_f\right) = 0$. Therefore, $\Pi_r^{CO} > \Pi_r^{CM}$ when $\gamma_{\mathrm{f}} < \gamma_{\mathrm{r}} - \sqrt{\frac{\gamma_{\mathrm{r}}^3}{\gamma_{\mathrm{r}} + \bar{\gamma}_f}}$, and the retailer chooses the marginal wholesale price and the quality such that the farmers do not compete with each other. ■

Proof of Proposition 4. (i) If $0 < \gamma_{\mathrm{f}} \leq \gamma_{\mathrm{r}} - \sqrt{\frac{\gamma_{\mathrm{r}}^3}{\gamma_{\mathrm{r}} + \bar{\gamma}_f}}$, Proposition 3 and Lemma 3 show that in the competition case, the retailer chooses

$$\frac{\partial^2 \Pi_r^{CM}}{\partial w_m^{CM2}} = -\frac{\mu^3\left(p_m \bar{\gamma}_f^2 \theta_r^{CM} + w_m^{CM}\left(\bar{\gamma}_f \theta_r^{CM}\left(3\bar{\gamma}_f \theta_r^{CM} + 6w_m^{CM}\mu + 4\sqrt{T}\right) + 2w_m^{CM}\mu\left(w_m^{CM}\mu + \sqrt{T}\right)\right)\right)}{\bar{\gamma}_f T^{3/2}} < 0 \tag{A.1}$$

$\theta_r^{C*} = \theta_r^{CO}$ and $w_m^{C*} = w_m^{CO}$ such that farmers do not compete with each other and the output quality, famer's profit and retailer's profit is the same as the benchmark case. Hence, $\theta^{C*} = \theta^{CO} = \theta^{B*}$, $\Pi_r^{C*} = \Pi_r^{CO} = \Pi_r^{B*}$, $\Pi_f^{C*} = \Pi_f^{CO} = \Pi_f^{B*}$.

(ii) If $\gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}} < \gamma_f < \bar{\gamma}_f$, Proposition 3 and Lemma 3 show that in the competition case, the retailer chooses $\theta_r^{C*} = \theta_r^{CM}$ and $w_m^{C*} = w_m^{CM}$ such that farmers competes with each other. Hence, the output quality is $\theta^{C*} = \theta^{CM}$, $\Pi_r^{C*} = \Pi_r^{CM}$, $\Pi_f^{C*} = \Pi_f^{CM}$.

(ii-a) Quality. Define $\hat{\theta} = \theta^{B*} - \theta^{CM} = p_m\mu\left(-\frac{1}{\gamma_r} + \frac{\gamma_r}{2\gamma_r\gamma_f - \gamma_f^2} - \frac{1}{\bar{\gamma}_f}\right)$. $\hat{\theta}$ is convex in γ_f since

$$\frac{\partial^2 \hat{\theta}}{\partial \gamma_f^2} = \frac{2p_m\mu\gamma_r\left(4\gamma_r^2 - 6\gamma_r\gamma_f + 3\gamma_f^2\right)}{\left(2\gamma_r - \gamma_f\right)^3\gamma_f^3} > 0$$

and additionally, $\hat{\theta}$ is minimized at $\gamma_f = \gamma_r$ Then solving for $\hat{\theta} = 0$, we can show that there exists a $\hat{\gamma}_f = \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}} < \gamma_r$ such that $\hat{\theta}\left(\hat{\gamma}_f\right) = 0$ Therefore, $\theta^{B*} < \theta^{C*}$ if $\gamma_f > \gamma_r - \sqrt{\frac{\gamma_r^3}{\gamma_r + \bar{\gamma}_f}}$.

(ii-b) Farmer's profit. $\Pi_f^{B*} - \Pi_f^{CM} = \frac{1}{2}p_m^2\mu^2\left(\frac{(\gamma_r - \gamma_f)(\gamma_r + \gamma_f)}{\gamma_f\left(-2\gamma_r + \gamma_f\right)^2} + \frac{\gamma_f - \bar{\gamma}_f}{\bar{\gamma}_f^2}\right) > 0.$ ■

Proof of Proposition 5. In the benchmark case, the supply chain profit $\Pi_r^{B*} + \Pi_f^{B*}$ decreases in γ_f since

$$\frac{d\Pi_r^{B*} + \Pi_f^{B*}}{d\gamma_f} = \frac{p_m^2\mu^2\left(6\gamma_r{}^3 - 9\gamma_r{}^2\gamma_f + 4\gamma_r\gamma_f{}^2 + \gamma_f{}^3\right)}{2\gamma_f{}^2\left(-2\gamma_r + \gamma_f\right)^3} < 0$$

In the competition case, when farmers need to compete with each other, the supply chain profit is $\Pi_r^{C*} + \Pi_f^{C*} = \Pi_r^{CM} + \Pi_f^{CM}$. $\Pi_r^{CM} + \Pi_f^{CM}$ decreases in γ_f since

$$\frac{d\Pi_r^{CM} + \Pi_f^{CM}}{d\gamma_f} = -\frac{p_m^2\mu^2}{2\bar{\gamma}_f^2} < 0$$

Additionally, when $\gamma_f = \bar{\gamma}_f$, $\Pi_r^{B*} + \Pi_f^{B*} - \left(\Pi_r^{CM} + \Pi_f^{CM}\right) = -\frac{p_m^2\mu^2\left(\gamma_r^3 + \gamma_r^2\bar{\gamma}_f - 2\gamma_r\bar{\gamma}_f^2 + \bar{\gamma}_f^3\right)}{2\gamma_r\bar{\gamma}_f\left(-2\gamma_r + \bar{\gamma}_f\right)^2} < 0$; when $\gamma_f = 0$,

$$\lim_{\gamma_f \to 0} \Pi_r^{B*} + \Pi_f^{B*} \to +\infty >$$
$$\Pi_r^{CM} + \Pi_f^{CM} = \frac{p_m^2\mu^2\left(\gamma_r + \bar{\gamma}_f\right)}{2\gamma_r\bar{\gamma}_f}$$

Hence, there must exist a $\tilde{\gamma}$ such that $\Pi_r^{B*} + \Pi_f^{B*} = \Pi_r^{CM} + \Pi_f^{CM}$. ■

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Data Availability

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Conflicts of Interest

Weihua Zhou is an editorial board member for the Journal of Systems Science and Systems Engineering and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no other competing interests.

Endnotes

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