Research on the Digital Transformation Model of Contract Farming Supply Chain Considering the Uncertainty of Technical Efficiency

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Abstract. With the rapid advancement of big data, AI, and IoT, smart agriculture is reshaping contract farming supply chains. Considering technology efficiency uncertainty and sales model heterogeneity, this study builds a two-player Stackelberg game model for the "enterprise + agricultural cooperative" supply chain to explore the cooperative's digital transformation technology adoption strategies and the selection mechanism between its independent technology purchase and enterprise technical assistance models. Results show an inverted U-shaped relationship between the cooperative's profit and revenue-sharing ratio: extremely low or high ratios favor independent technology purchase for digital transformation, while moderate ratios prefer enterprise technical assistance. Technically weak cooperatives should choose the assistance model even with low revenue-sharing ratios, as they can leverage enterprises' high-level technology investment to optimize revenue.This study provides guidance for the digital transformation of cooperatives and the contract design of enterprises.

Keywords: Agriculture Supply Chain; Digital Transformation; Contract design

1 Introduction

Smart agriculture technology serves as a novel form of productive force driving the digital transformation of the agricultural industry. By virtue of the in-depth integration of Internet of Things (IoT) devices and big data technologies, it enables the intelligent management of the entire process of agricultural cultivation, sowing, field management and harvesting. However, the adoption rate of smart agricultural technologies among farmers remains generally low. For instance, less than 10% of farmers in Africa have access to digital devices[1]. The adoption rate among smallholder farmers in Ghana remains at a low level [2]. Low adoption willingness of small farmers has slowed agricultural digital transformation [3]. With high costs and uncertain input-output returns as key barriers. Thus, promoting technology adoption in agricultural supply chains is critical for advancing smart agriculture.

In the "cooperative + agricultural enterprise" order-based supply chain, cooperatives adopt two models for smart technology adoption and digital transformation.

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Independent technology purchase: Enterprises act as service providers; cooperatives pay for technologies/supporting services, hold independent sales rights, but bear investment costs and output uncertainty risks. Enterprise technical assistance: Cooperatives use enterprise-provided technology for free but must deliver outputs to enterprises for contract-based sales, reducing technology risks but limiting profit margins. These models reflect cooperatives' trade-offs between investment costs, application risks and sales autonomy during digital transformation.

At present, cooperative digital transformation is constrained by high investment costs and uncertain technology efficiency.This study constructs Stackelberg game models under the "independent technology purchase" and "enterprise technology assistance" mode to explore cooperative technology adoption choices and enterprise contract design mechanisms.This study provides new perspectives for cooperatives to achieve digital transformation. It also offers scientific decision-making guidance for agricultural enterprises.

The rest of the paper is structured as follows: Section 2 reviews literature on contract farming technology introduction strategies; Section 3 elaborates research hypotheses and constructs the game model; Section 4 explores optimal contract mechanisms and cooperative technology adoption choices; Section 5 presents conclusions and implications.

2 Literature Review

In recent years, with the rapid development of contract farming, relevant scholars have conducted a series of studies on contract design and technology introduction strategies.In terms of contract mechanism design, existing literature has conducted in-depth discussions on flexible supply contracts[4] deferred payment contracts[5], two-stage hierarchical pricing contracts[6], and dynamic payment contracts[7].In terms of technology introduction strategies, scholars have focused on the strategies and impacts of technology introduction in agricultural product supply chains.For example, they have analyzed the mechanism of blockchain in combating agricultural product adulteration[8] and enhancing consumers' purchase intention[9].They have also explored optimal technology investment decisions[10].

Although existing studies have discussed contract design in contract farming, they have not fully examined the interactive impact of technology introduction on production and sales processes.Moreover, few studies have focused on technology adoption models of cooperatives.Therefore, this paper comprehensively considers the uncertainty of technology efficiency and differences in sales models to explore the following research questions: (1)What is the cooperatives' technology adoption strategy under the background of uncertain technology efficiency? (2) How does the agricultural enterprise's contract design affect the cooperatives' planting efforts, the quality of agricultural product outputs, as well as the cooperatives' profits and technology adoption decisions?

3 The Model

This study focuses on agricultural cooperatives' digital transformation technology adoption decisions. It constructs a two-player Stackelberg game model involving cooperatives (C) and enterprises (E), characterizing their strategic interactions in technology provision and adoption. Specifically, as the leader, the enterprise determines the technology provision scheme to maximize its interests; as the follower, the cooperative decides its planting effort level and technology adoption mode. Two adoption modes are considered with key differences: under the independent technology purchase mode (superscript P), the enterprise only sells technology for usage fees without participating in product sales, and the cooperative sets the sales price. In contrast, under the enterprise technology assistance mode (superscript A), the enterprise provides free technical assistance. In return, the cooperative surrenders autonomous pricing power and gains revenue per the contracted profit-sharing ratio.

3.1 Agricultural Product Quality Improvement

Agricultural digital transformation involves multiple emerging technologies; this study focuses on agricultural IoT technology, whose devices automate regulatory operations. Agricultural product quality improvement depends on the cooperative's planting effort and the enterprise's technology level: IoT enhances quality indirectly by optimizing growth environments, while planting effort drives it directly via precision management. Total quality improvement is the sum of these two factors. Let e denote the cooperative's planting effort level, with an effort cost of $e^2/2$.Let θ represent the technology level provided by the enterprise, with a technology cost of $\theta^2/2$.

In Model P, the cooperative must pay a per-unit output technology service fee v to use IoT technology. Technology efficiency is uncertain due to the cooperative's knowledge and skill constraints; $\alpha(0<\alpha<1)$ is introduced to aptures technology-to-quality conversion efficiency. In this model,the quality improvement brought by the technology is $\alpha\theta$, and total product quality improvement is $\alpha\theta+e$.The cooperative retains independent sales rights, with potential market size a. In Model A, the cooperative uses IoT technology and guidance for free. The enterprise sells products and shares a revenue ratio γ with the cooperative. Expert guidance eliminates technology efficiency uncertainty, so technology-driven quality improvement is θ, and total product quality improvement is $\theta+e$.Under this model, the enterprise sales products. Benefiting from the enterprise's market influence, the corresponding potential market size is φa, where $\varphi(\varphi>1)$ represents the growth in potential market size driven by the enterprise's sales efforts.

3.2 Decision Sequence

Under the mode P, the sequence of decisions is as follows: first, the enterprise determines the technology level θ and technology service fee v; second, the cooperative decides on the planting effort level e and sales price p_c.Under the the mode A, the decision sequence is as follows: first, the enterprise determines the technology level θ and sales price p_e based on the revenue-sharing ratio γ (the proportion of revenue allocated by the enterprise to the cooperative); second, the cooperative decides on the planting effort level e.

3.3 Profit Functions

Drawing on the research by Shin et al.[11], quality improvement can drive an increase in market demand.let $m(0 < m < 1)$ denotes the consumer's quality preference coefficient.The demand function under the mode P and mode A is expressed as follows:

$$d^P = a - p_c + m(\alpha\theta + e) \tag{1}$$

$$d^A = \varphi a - p_e + m(\theta + e) \tag{2}$$

Under Mode P, the enterprise's profit is derived from technology sales, while the agricultural cooperative's profit stems from revenue by agricultural product sales. The profit functions as follows:

$$\pi_e^P = vd^P - \frac{1}{2}\theta^2 \tag{3}$$

$$\pi_c^P = (p_c - v)d^P - \frac{1}{2}e^2 \tag{4}$$

Under Mode A, the enterprise's profit is derived from product sales, while the agricultural cooperative's profit stems from the profit share of the enterprise's sales revenue. The profit functions as follows:

$$\pi_e^A = (1-\gamma)p_e d^A - \frac{1}{2}\theta^2 \tag{5}$$

$$\pi_c^A = \gamma p_e d^A - \frac{1}{2}e^2 \tag{6}$$

4 Analysis

In this section, we first solve for the equilibrium prices under the two technology adoption models and obtain the payoffs of the enterprise and the agricultural cooperative. Then, we analyze the technology adoption strategies.

The equilibrium decisions of the model P model as follows:

$$\theta^{P*} = \frac{a\alpha\, m}{4-\alpha^2 m^2 - 2m^2}, \quad v^{P*} = \frac{a\left(2-m^2\right)}{4-\alpha^2 m^2 - 2m^2}, \quad p_c^{P*} = \frac{a\left(3-m^2\right)}{4-\alpha^2 m^2 - 2m^2},$$

$$e^{P*} = \frac{am}{4-\alpha^2 m^2 - 2m^2}$$

The payoff of the enterprise and the agricultural cooperative of the model P as follows:

$$\pi_c^{P*} = \frac{a^2\left(2-m^2\right)}{2\left(\alpha^2 m^2 + 2m^2 - 4\right)^2}, \quad \pi_e^{P*} = \frac{a^2}{2\left(4-\alpha^2 m^2 - 2m^2\right)}$$

The equilibrium decisions of the model A as follows:

$$e^{A*} = \frac{a\,\gamma\, m\phi}{2-m^2-\gamma m^2}, \quad p_e^{A*} = \frac{a\phi}{2-m^2-\gamma m^2}, \quad \theta^{A*} = \frac{a\, m\phi(1-\gamma)}{2-m^2-\gamma m^2}$$

The payoff of the enterprise and the agricultural cooperative of the model A as follows:

$$\pi_e^{A*} = \frac{a^2\phi^2(1-\gamma)}{2\left(2-m^2-\gamma m^2\right)}, \quad \pi_c^{A*} = \frac{a^2\gamma\phi^2\left(2-3\gamma m^2\right)}{2\left(2-m^2-\gamma m^2\right)^2}$$

Corollary 1 $\frac{\partial \pi_e^{A*}}{\partial \gamma} < 0$ holds constantly; when $\gamma < \frac{2-m^2}{m^2(5-3m^2)}$, $\frac{\partial \pi_c^{A*}}{\partial \gamma} < 0$;conversely, $\frac{\partial \pi_c^{A*}}{\partial \gamma} > 0$.

The enterprise's profit decreases as the revenue-sharing ratio increases. This is because profit sharing constitutes the enterprise's sole source of profit in this model, and a direct increase in the cooperative's profit share will lead to a reduction in the profit retained by the enterprise. However,the profit derived from the digital transformation of cooperatives does not exhibit a monotonically increasing relationship with the profit-sharing ratio. When the ratio exceeds a certain threshold, the cooperative's profit will decrease as the ratio rises. This is because an excessively high sharing ratio will squeeze the enterprise's profit margin. To cover costs, the enterprise has to lower its technology level, which in turn results in a significant decline in market demand. At this point, even if the cooperative increases its investment in planting efforts, it cannot offset the losses caused by the decline in smart argriculture technology level, ultimately leading to a drop in the cooperative's profit.

Proposition 1 When $\gamma \in (0,\gamma_1)$, $\theta^{P*} < \theta^{A*}$; conversely, $\theta^{P*} > \theta^{A*}$ .Where $\gamma_1 = \dfrac{\alpha m^2 - 2\alpha + \phi(4-\alpha^2 m^2 - 2m^2)}{-\alpha m^2 + \phi(4-\alpha^2 m^2 - 2m^2)}$.

When the profit-sharing ratio is relatively low, the level of technology invested by the enterprise under the A model is higher than that under the P model.This is because the enterprise retains a relatively high profit margin in this scenario, leading to a high marginal return on technology investment.Moreover, since the enterprise holds the power to set the sales price of agricultural products, it can cover technology costs through price adjustments and thus tends to invest in technology to expand market demand and increase profits.In contrast, under the independent purchase model (P model), the effectiveness of technology investment is weakened due to the uncertainty in the cooperative's technology conversion efficiency, resulting in a lower optimal level of digitalization achieved by cooperatives.

Proposition 2 When $\gamma \in (0,\gamma_2)$, $e^{P*} > e^{A*}$; conversely, $e^{P*} < e^{A*}$ .Where $\gamma_2 = \dfrac{2-m^2}{m^2\,\phi(4-\alpha^2 m^2 - 2m^2)}$.

When the profit-sharing ratio is relatively low, the cooperative's effort input under the P model is higher than that under the A model.This is because the cooperative under the assistance model receives a relatively low profit share, which dilutes the marginal return on its planting effort. Therefore, although cooperatives have undergone digital transformation, they have to adopt a low-price strategy. Furthermore, the enterprise's pricing strategy further squeezes the cooperative's profit margin. As a result, the cooperative is unwilling to invest in planting effort and instead adopts a technology free-riding strategy to benefit from the quality improvement brought by the enterprise's technology input.As the profit-sharing ratio increases, the marginal return on the cooperative's effort rises. The combined effect of effort input and technology input becomes prominent, and the cooperative's willingness to invest is accordingly enhanced.

Proposition 3 When $\alpha \in (0,\alpha_1)$, $p_c^{P*} < p_e^{A*}$; conversely, $p_c^{P*} > p_e^{A*}$ .Where $\alpha_1 = \dfrac{\sqrt{\phi(4-2m^2)-\left(3-m^2\right)(2-m^2-\gamma m^2)}}{2\phi m^2}$.

When the cooperative has weak technology application capacity, the enterprise will set a higher price. Although the cooperative sets prices independently under the technology purchase model, low technology efficiency limits quality improvement; a price increase would reduce sales and erode profits, forcing a low-price strategy. In contrast, full-process guidance under the assistance model eliminates technology efficiency uncertainty, fully converting investment into quality gains. Consumers pay premiums for high quality, so price-increase gains outweigh sales losses, leading the enterprise to set higher prices than the cooperative.When the cooperative has strong technology application capacity, it will set higher prices under the independent model. It can effectively convert investment into quality improvement and retain all price-increase gains without profit sharing, creating incentives for high prices. For the enterprise, price-increase gains must be shared and will cause sales losses, resulting in lower prices than the cooperative under the independent model.

Proposition 4 When $\gamma < \frac{1}{2}$ and $\alpha \in (0, \alpha_3)$, $(\alpha\theta + x)^{P*} < (\theta + x)^{A*}$; conversely, $(\alpha\theta + x)^{P*} > (\theta + x)^{A*}$, where $\alpha_3 = \sqrt{\frac{(2 - m^2(1-\gamma)}{2 - \gamma m^2}}$.

When the profit-sharing ratio offered by the enterprise to the cooperative is relatively low and the cooperative's technology efficiency is relatively low, the final quality of agricultural products under the assistance model will be higher than that under the technology purchase model.This is because when the enterprise retains a relatively high profit margin, it has sufficient funds for technology investment. Meanwhile, given the cooperative's low technology efficiency, technical assistance can make up for the deficiency in the cooperative's own capabilities, thereby improving the final quality of agricultural products.Under such circumstances, the digital transformation implemented by cooperatives have contributed to the enhancement of the final quality of agricultural products.

Proposition 5 When $\gamma \in (0, \gamma_1)$, $\pi_c^{P*} > \pi_c^{A*}$; when $\gamma \in (\gamma_1, \min\{\gamma_2, 1\})$, $\pi_c^{P*} < \pi_c^{A*}$; when $\gamma \in (\min\{\gamma_2, 1\}, 1)$, $\pi_c^{P*} > \pi_c^{A*}$.Where

$$\gamma_1 = \frac{-B - \sqrt{B^2 - 4m^4\left(2 - m^2\right) + 3\phi^2 m^2\left(\alpha^2 m^2 + 2m^2 - 4\right)^2 (2 - m^2)^3}}{2m^4\left(2 - m^2\right) + 3\phi^2 m^2\left(\alpha^2 m^2 + 2m^2 - 4\right)^2};$$

$$\gamma_2 = \frac{-B + \sqrt{B^2 - 4m^4\left(2 - m^2\right) + 3\phi^2 m^2\left(\alpha^2 m^2 + 2m^2 - 4\right)^2 (2 - m^2)^3}}{2m^4\left(2 - m^2\right) + 3\phi^2 m^2\left(\alpha^2 m^2 + 2m^2 - 4\right)^2};$$

$$B = -2m^2(2 - m^2)^2 - 2\phi^2\left(\alpha^2 m^2 + 2m^2 - 4\right)^2.$$

Under the assistance model, the cooperative earns higher profits via independent technology purchase when the profit-sharing ratio is low: a low ratio squeezes its margin, yet independent purchase allows it to sell through the enterprise's platform and leverage autonomous pricing—with pricing power dominating profits, technology support merits are negligible, driving independent transformation. Counterintuitively, an excessively high ratio also leads the cooperative to prefer independent purchase, as it drastically reduces the enterprise's profits, prompting cuts to technology investment and free-riding on the cooperative's planting efforts, resulting in lower returns under assistance. Only a moderate profit-sharing ratio under assistance yields higher profits for the cooperative. It covers the cooperative's effort costs and technology investment, enabling joint quality improvement efforts; thus, the cooperative pursues digital transformation and profit growth through assistance.

To show the impact of the profit-sharing ratio on the cooperative's choice of technology adoption, parameter values are assigned with reference to the aforementioned analysis. With values set as $m = 0.9$, $a = 0.3$ $\alpha = 0.9$, $\varphi = 1.2$, and substituted into the results, MATLAB is used for simulation and plotting. As illustrated in Figure 1.

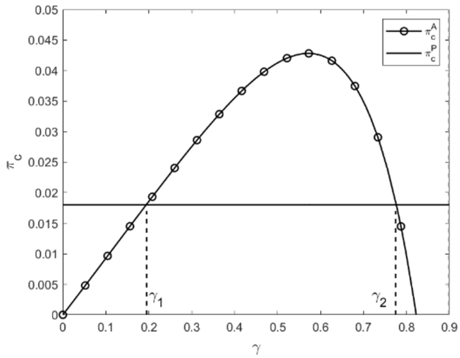

Fig. 1. Cooperative Profits Under Two Technology Adoption Modes

5 Conclusion

This study focuses on the digital transformation strategies of cooperatives in the contract farming supply chain. By constructing Stackelberg game models under two modes—independent technology purchase and enterprise-led technology support—it analyzes the impact of key factors such as profit-sharing ratio and technology utilization efficiency on the equilibrium decisions of both parties. The results indicate that: the profit of cooperatives under the technology support mode exhibits an inverted U-shaped relationship with the profit-sharing ratio. When the ratio is excessively low or high, cooperatives gain more advantages by choosing the independent technology purchase mode; conversely, a moderate sharing ratio makes the technology support mode more conducive to their digital transformation. For cooperatives with weak technical capabilities, accepting enterprise-led technology support with a low profit-sharing ratio can achieve optimal returns by leveraging the enterprises' high-level technology investment. The core of cooperatives' digital transformation lies not in the profit maximization of a single entity, but in the dynamic balance between technology investment and planting efforts of both supply chain parties. Only by avoiding one-sided free-riding behavior can the value of smart agriculture technologies be fully unleashed.

For enterprises, when setting the profit-sharing ratio, they must keep it within a moderate range that covers their technology costs while fully motivating cooperatives' planting efforts. Further, differentiated contracts should be designed based on cooperatives' technical capabilities. For cooperatives, they need to accurately match technology adoption models to their own technical capabilities. Less competent cooperatives should prioritize technology assistance, for instance, rural cooperatives in Africa can optimize returns by obtaining free IoT monitoring devices through assistance with enterprises. In contrast, highly competent cooperatives should choose independent technology purchase when the profit-sharing ratio is excessively low or high. A case in point is large-scale cooperatives in eastern China, which can independently procure IoT equipment, set prices based on local market demand, and maximize profits.

This study is limited by its inadequate consideration of market demand fluctuations (e.g., cyclical changes in agricultural product prices, demand shocks from public health emergencies) and agricultural output uncertainty (e.g., yield impacts of natural disasters and pests). Future research can introduce random variables (e.g., defining fluctuation probability distributions based on historical demand/yield data) to characterize uncertainty, exploring cooperatives' technology adoption strategies and risk-sharing mechanisms. Additionally, multi-agent competition and cooperation are prevalent in real-world contract farming supply chains; thus, investigating cooperatives' technology adoption strategies in competitive environments presents a promising research direction.

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