

A Stackelberg Game Model for Procurement Pricing in the Upstream Sago Agro-Industry Supply Chain

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INFO ARTIKEL

Riwayat Artikel:

Diterima: 01-09-2026

Disetujui: 30-10-2026

Kata Kunci:

Agroindustri Sagu;
Harga Pengadaan;
Keputusan Pasokan;
Rantai Paok;
Stackelberg Game.

Keywords:

Procurement Pricing;
Sago Agro-Industry;
Stackelberg Game;
Supply Chain;
Supply Decision.

ABSTRAK

Abstrak: Penelitian ini bertujuan mengembangkan model analitik *Stackelberg game* dengan industri sebagai *leader* dan petani sebagai *follower*. Model diselesaikan secara analitis menggunakan *backward induction*. Ilustrasi numerik diberikan berdasarkan karakteristik industri sagu dari tinjauan literatur dan hasil observasi lapangan. Hasil perhitungan menunjukkan harga keseimbangan pengadaan bahan baku sebesar Rp 61.000 per tual sagu. Pada harga ini, setiap petani memasok 16 tual sagu per bulan sehingga menghasilkan pasokan agregat sebesar 400 tual. Petani dan industri sama-sama memperoleh keuntungan pada kondisi keseimbangan. Industri memperoleh keuntungan agregat yang lebih tinggi dalam struktur *leader-follower* ini. Hasil penelitian menunjukkan penetapan harga pengadaan secara strategis membentuk pasokan petani dan profitabilitas industri sagu. Penelitian ini memberikan kerangka dasar dalam mengkaji hubungan pengadaan dalam rantai pasok hulu agroindustri.

Abstract: This study aims to develop an analytical Stackelberg game model in which the processing industry acts as the leader and farmers as followers. The model is solved analytically using backward induction. A numerical illustration is provided based on sago industry characteristics obtained from the literature and field observations. The results show an equilibrium raw material procurement price of IDR 61,000 per sago log. At this price, each farmer supplies 16 sago logs per month, resulting in an aggregate supply of 400 logs. Both farmers and the processing industry obtain positive profits at equilibrium. The processing industry obtains higher aggregate profit under this leader-follower structure. The results show how strategic procurement pricing shapes farmer supply and the profitability of the sago processing industry. This study provides a baseline framework for examining procurement relationships in the upstream sago agro-industry supply chain.



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A. INTRODUCTION

Sago has considerable potential as a food and agro-industrial resource in Indonesia. Sago starch can be processed into various food products and other derivatives, creating opportunities for value addition and local economic development (Elida et al., 2021; Murod et al., 2018). Sago also has an important role in food diversification. The Indonesian government has encouraged the food industry to replace part of imported wheat flour with sago starch, which may increase demand for sago-based products and benefit sago farmers (Trisia et al., 2021). However, increasing demand for sago starch raises concerns about the availability of sago palms and raw materials for processing industries. These conditions underscore the importance of examining procurement and supply relationships in the upstream sago agro-industry to balance supply and demand.

The upstream sago agro-industry supply chain involves procurement between processing industries and independent farmers. Farmers harvest sago trees and sell the resulting logs to processing industries, which process them into wet or dry sago starch (Murod et al., 2018; Pratama et al., 2018). Although processing industries may have their own plantations, external suppliers, including farmers and traders, also contribute to raw material requirements (Khotijah et al., 2020). In this relationship, the processing industry sets the procurement price, while farmers determine their supply in response to the price and harvesting, labour, and transportation costs. Thus, procurement price, farmer supply quantity, harvesting costs, and processing costs are relevant variables for examining upstream procurement interactions. However, farmers may have limited influence over procurement terms (Riza et al., 2017).

Previous studies have examined several aspects of the sago supply chain, but their analytical focus differs from the procurement interaction discussed in this study. Herlon et al. (2022) analyzed the operational mechanisms and supply chain flow of a large-scale sago processing industry in the Meranti Islands. Juwairiah et al. (2023) examined management and processing capacity in a small-scale sago flour processing enterprise using the SCOR framework. Khotijah et al. (2020) investigated the value chain and sustainability of a medium-scale sago industry. Anwar & Djatn, (2018) proposed a responsive supply chain system for micro- and small-sized sago-based food industries by identifying and analyzing supply chain entities and requirements through input-process-output analysis. These studies provide empirical insights into supply chain structure, processing capacity, responsiveness, and value chain relationships, but do not explicitly examine how procurement prices set by processing industries affect farmers' supply decisions.

In the Indonesian context, other studies have applied analytical approaches to specific supply chain problems. Anwar et al. (2022) developed a Bayesian network model to identify key supply chain risk drivers affecting the performance of the sago starch agro-industry under uncertainty and interdependencies among risk factors.

Yusmiati et al. (2023) developed a fuzzy Shapley cooperative game model for profit distribution among farmers, traders, and wet sago starch industries under uncertainty and risk. Their results showed a more favorable profit allocation than the existing distribution. More recently, Anwar et al. (2025) developed an optimization model to support coordination between sago-based food MSMEs and sago starch suppliers through joint operational decisions. These studies show that analytical methods have addressed risk management, profit distribution, and operational coordination in the sago supply chain. However, procurement pricing as a strategic interaction between processing industries and farmers remains less explored. This gap is particularly relevant because procurement decisions involve sequential interactions between buyers and suppliers with different bargaining positions.

Many agricultural supply chains involve sequential decisions between participants with different levels of bargaining power. Wang et al. (2022) showed that leading enterprises can influence the decisions of other supply chain participants, while agricultural suppliers respond to the prices or conditions established by these firms. A similar structure was examined by Jin et al. (2024), in which leading enterprises determine procurement conditions such as quantity, quality, and purchase price, while small farmers respond through their supply decisions. This relationship reflects a leader-follower structure, with the leader making decisions while anticipating the followers' responses. The Stackelberg game provides an analytical framework for representing this sequential decision-making process.

To address the identified research gap, this study aims to develop a Stackelberg game model for procurement pricing in the upstream sago agro-industry supply chain. The processing industry acts as the Stackelberg leader that determines the procurement price of raw sago logs, while homogeneous farmers act as followers who determine their optimal supply quantities in response to the announced price. The model considers a baseline procurement setting and derives the farmers' reaction function and the processing industry's optimal procurement decision under an interior equilibrium condition. The study makes two main contributions. First, it develops an analytical Stackelberg game model that explicitly represents the sequential procurement interaction between a processing industry and farmers. Second, the model yields closed-form expressions for the equilibrium procurement price and farmers' supply decisions, providing an analytical basis for interpreting the procurement interaction. The proposed model therefore provides a tractable baseline framework for analyzing procurement pricing and supply decisions in the upstream sago agro-industry supply chain.

B. METHOD

This study employs a quantitative research approach based on analytical game-theoretic modeling using a Stackelberg game to represent sequential procurement decisions between a sago starch processing industry and independent farmers. The processing industry acts as the leader by determining the procurement price of raw sago logs, while farmers act as followers by deciding their supply quantities in response to the announced price. The model incorporates farmer production costs, processing industry operating costs, the conversion rate of raw sago logs into processed starch, the downstream selling price, and farmers' harvesting capacity. The profit-maximization problems of both actors are formulated to determine the equilibrium procurement price and supply decisions. Model formulation is informed by relevant literature and field observations concerning the sago supply chain, procurement relationships, processing activities, and economic characteristics. The numerical parameters are empirically informed and economically plausible, serving as an illustrative example rather than representing the exact operating conditions of a specific processing plant.

The model is solved analytically using backward induction by first deriving the farmers' profit-maximizing supply response to the procurement price and subsequently incorporating this reaction function into the processing industry's profit function. The optimal procurement price is then determined by anticipating farmers' responses, and the Stackelberg equilibrium is obtained through analytical derivation. The solution is verified using the second-order condition and interior equilibrium feasibility conditions. A numerical illustration is subsequently conducted by substituting the selected parameter values into the equilibrium expressions to evaluate the procurement price, individual farmer supply, and aggregate supply.

C. RESULTS AND DISCUSSION

1. Problem Description

The proposed model considers an upstream sago agro-industry supply chain consisting of a single sago starch processing industry and multiple homogeneous sago farmers. The processing industry procures raw sago logs from farmers and converts them into sago starch for sale in the downstream market. The processing industry acts as the Stackelberg leader by determining the procurement price, whereas farmers act as followers who determine their supply quantities after observing the announced price. The model focuses on the strategic procurement pricing interaction between the processing industry and farmers. The objective is to determine the Stackelberg equilibrium consisting of the optimal procurement price set by the processing industry and the corresponding supply decisions of farmers.

2. Model Assumptions and Notations

Decision variables

- p : Procurement price of fresh sago logs determined by the sago industry.
- q : Supply quantity of a representative farmer
- Q : Aggregate supply of raw sago logs

Parameters

- q^{max} : Maximum harvesting capacity of an individual farmer during the planning period.
- N : Number of homogeneous farmers.
- P : Selling price of processed sago starch.
- α : Conversion rate from fresh sago logs to processed sago starch.
- c : Baseline marginal production cost of farmers.
- k : Marginal production cost coefficient of farmers ($k > 0$).
- d : Marginal processing cost coefficient of the processing industry ($d \geq 0$).

Function and profit measures

- $C_f(q)$: Farmer's production cost function.
- $C_L(q)$: Sago processing industry's operating cost function.
- π_f : Profit of an individual farmer.
- π_L : Profit of the sago processing industry.

The underlying modeling assumptions are then presented as follows:

- A1 : The processing industry acts as the Stackelberg leader by setting the procurement price before farmers make supply decisions.
- A2 : Farmers act as Stackelberg followers and determine their individual supply quantities after observing the announced procurement price.
- A3 : The supply chain consists of N homogeneous farmers. Each farmer has a maximum harvesting capacity of q^{max} during the planning period, reflecting the limited number of mature sago palms available for harvest. The aggregate supply is given by $Q = Nq$.
- A4 : The selling price of processed sago starch (P) is assumed to be exogenous.
- A5 : The conversion rate from fresh sago logs to processed sago starch is constant and equal to α .
- A6 : The farmer's production cost is represented by $C_f(q) = cq + \frac{1}{2}kq^2$, capturing increasing marginal harvesting, labor, and transportation costs. This simple quadratic formulation offers a tractable representation of farmers' harvesting costs and aligns with previous supply chain studies (Agbo et al., 2015; Jin et al., 2024).
- A7 : The processing industry's operating cost is represented by $C_L(Q) = \frac{1}{2}dQ^2$

3. Farmer's Optimization Problem

Given the procurement price p , each farmer chooses the supply quantity q to maximize profit

$$\max_{0 \leq q \leq q^{max}} \{\pi_f(q) = pq - C_f(q)\}, \quad (1)$$

With the quadratic cost function, the first-order condition for an interior solution gives $p - c - kq = 0$, and hence

$$q^*(p) = \frac{p-c}{k} \quad (2)$$

For this interior solution to be economically and physically feasible, two conditions must be satisfied. First, the farmer must supply a positive quantity. Since $k > 0$, the condition $q^*(p) > 0$ implies $\frac{p-c}{k} > 0$ which implies $p > c$. Thus, the procurement price must exceed the farmer's baseline marginal harvesting cost c for a positive supply response to occur. Second, the interior solution must remain below the farmer's maximum harvesting capacity.

The condition $q^*(p) < q^{max}$ gives $\frac{p-c}{k} < q^{max}$ which implies $p < c + kq^{max}$. This means that the procurement price must remain below the price level at which the farmer would reach the maximum harvesting quantity q^{max} . Combining these two conditions gives the interior price region $c < p < c + kq^{max}$. Within this region, the farmer's optimal supply is determined by the interior reaction function as in Equation (2). While for outside this region, the farmer's supply is determined by the boundary conditions, namely zero supply when $p \leq c$ and maximum supply q^{max} when $p \geq c + kq^{max}$. Considering the harvesting capacity constraint, the farmer's reaction function can therefore be expressed as

$$q^*(p) = \begin{cases} 0, & p \leq c, \\ \frac{p-c}{k}, & c < p < c + kq^{max}, \\ q^{max}, & p \geq c + kq^{max}. \end{cases} \quad (3)$$

The subsequent Stackelberg analysis focuses on the interior equilibrium, for which the capacity constraint is non-binding. Thus,

$$q^*(p) = \frac{p-c}{k}, \quad c < p < c + kq^{max} \quad (4)$$

With N homogeneous farmers, the aggregate supply is

$$Q^* = Nq^*(p) = N \frac{p-c}{k} \quad (5)$$

4. Processing Industry Optimization Problem

The processing industry, as the Stackelberg leader, determines the procurement price p anticipating the farmers' optimal response derived in the previous subsection. The industry's profit is

$$\pi_L(p) = (\alpha P - p)Q(p) - C_L(Q(p)), \quad C_L(Q) = \frac{1}{2}dQ^2 \quad (6)$$

Defining $A = N/k$ and substituting $Q(p)$ yields

$$\pi_L(p) = A(\alpha P - p)(p - c) - \frac{1}{2}dA^2(p - c)^2 \quad (7)$$

The first-order condition for the optimal procurement price is

$$\frac{d\pi_L}{dp} = A(\alpha P + c - 2p) - dA^2(p - c) = 0, \quad (8)$$

which gives the closed-form solution

$$p^* = \frac{\alpha P + c + dAc}{2 + dA} \quad (9)$$

5. Stackelber Equilibrium

The Stackelberg equilibrium is obtained by substituting the optimal procurement price p^* into the farmers' reaction function. Under the interior equilibrium condition, the equilibrium supply quantity per farmer are given by Equation (4) and the aggregate supply are given by Equation (5). The interior equilibrium is valid only if the resulting procurement price satisfies $c < p < c + kq^{max}$. The lower bound ensures a positive supply response, whereas the upper bound ensures that the farmers' harvesting capacity is not binding. If this condition is violated, the equilibrium may occur at a boundary with zero or capacity-constrained supply, which is beyond the scope of the present analysis. The optimality of the procurement price is verified by the second derivative of the processing industry's profit function:

$$\frac{d^2\pi_L}{dp^2} = -2A - dA^2 < 0 \quad (10)$$

For $A > 0$ and $d \geq 0$. Thus, the industry's profit function is strictly concave in p , confirming that p^* is the unique global maximizer within the interior feasible region.

6. Numerical Illustration

Parameter setting

The numerical illustration demonstrates the application of the proposed Stackelberg model using parameter values informed by previous studies and recent field observations. The numerical example illustrates the model's analytical behavior using economically plausible parameter values rather than reproducing the exact operating conditions of a particular processing industry. Since empirical estimates of the cost coefficients are unavailable, k and d are specified to represent increasing marginal harvesting and processing costs, respectively.

In Kepulauan Meranti Regency, Riau, one sago log is approximately 1 meter long and weighs about 100 kg, with a conversion yield of approximately 18% from fresh logs to dry sago starch, consistent with Pratama *et al.*, (2018). Khotijah *et al.*, (2020) reported a normal production level of approximately 52 tons of dry sago starch per month. However, recent field observations indicate that current production is lower than in previous years. Therefore, this study adopts 52 tons per month as a benchmark for maximum processing capacity. Field observations also indicate that approximately 50% of the raw material requirement is supplied by surrounding independent farmers. Accordingly, the benchmark capacity requires approximately 2,888.89 logs per month, of which 1,444.44 logs are supplied by independent farmers. Assuming 25 active farmers, the resulting baseline harvesting capacity is approximately 58 logs per farmer per month. While the procurement price of good-quality sago logs is estimated at IDR 55,000 to IDR 65,000 per log based on recent field observations. To simplify the

analysis, monetary values are normalized by IDR 50,000 per log. Accordingly, the reference procurement price range is represented by $p \in [1.10, 1.30]$. The selling price of processed sago starch is estimated at approximately IDR 650,000 per 50-kg bag, based on Ehara (2024) and recent field observations, corresponding to a normalized value of $P = 13$. Table 1 summarizes the parameter values used in the numerical illustration.

Tabel 1. Parameter Values

Parameter	Value	Unit	Parameter	Value	Unit
P	14	n.m.u/50 kg starch	k	0.02 [#]	n.m.u/log ²
α	0.18	-	d	0.002 [#]	n.m.u/log ²
N	25	farmers	q^{max}	58	Logs/farmer/mont h
c	0.90	n.m.u/log			

Stackelberg equilibrium

The optimal procurement price is obtained from Equation (9). Thus, $A = \frac{N}{k} = \frac{25}{0.02} = 1250$. Therefore

$$p^* = \frac{(0.18)(13) + 0.9 + (0.002)(1250)(0.9)}{2 + (0.002)(1250)} = 1.22$$

The corresponding harvesting-capacity threshold is $c + kq^{max} = 0.9 + 0.02(58) = 2.06$. Since $0.9 < p^* = 1.22 < 2.06$, the interior equilibrium condition is satisfied. Under the adopted normalization, the equilibrium procurement price corresponds to approximately IDR 61,000 per log. This value lies within the reported reference procurement price range of IDR 55,000 to 65,000 per log and is therefore used as an analytical benchmark for the numerical illustration.

The equilibrium supply of each farmer is $q^* = \frac{p^* - c}{k} = \frac{1.22 - 0.9}{0.02} = 16$ logs per farmer per month. Since $q^* = 16 < q^{max} = 58$, the harvesting capacity constraint is non-binding. The aggregate supply is therefore $Q^* = Nq^* = 25(16) = 400$ log per month. Assuming an average weight of 100 kg per log and a conversion yield of 18%, the resulting procurement corresponds to approximately 40 tons of raw sago logs and 7.2 tons of dry sago starch per month. The profit of an individual farmer is

$$\begin{aligned}\pi_f &= p^* q^* - C_f(q^*) \\ &= (1.22)(16) - \left[0.9(16) + \frac{1}{2}(0.02)(16)^2 \right] \\ &= 2.56\end{aligned}$$

Thus, the aggregate profit of the farmers is $N\pi_f = 25(2.56) = 64.00$.

The processing industry's profit is

$$\begin{aligned}\pi_L &= \alpha P Q^* - p^* Q^* - \frac{1}{2} d (Q^*)^2 \\ &= (0.18)(13)(400) - (1.22)(400) - \frac{1}{2}(0.002)(400)^2 \\ &= 288.00\end{aligned}$$

The numerical illustration therefore shows that the equilibrium generates positive profits for both the farmers and the processing industry. The aggregate profit of the processing industry is higher than the combined profit of the farmers under the assumed leader-follower procurement structure.

Numerical illustration of the farmers' supply response

To further illustrate the farmers' response to the procurement price, the reaction function is evaluated at several price levels:

$$q^*(p) = \begin{cases} 0, & p \leq 0.9 \\ \frac{p-0.9}{0.02}, & 0.9 < p < 2.06 \\ 58, & p \geq 2.06 \end{cases}$$

Table 2 presents selected values.

Tabel 2. Farmers' supply response under different procurement prices

Procurement price p	Calculation	Supply q	Remarks
0.90	$(0.90-0.90)/0.02$	0	No supply
1.00	$(1.00-0.90)/0.02$	10	Interior solution
1.10	$(1.10-0.90)/0.02$	15	Interior solution
1.22	$(1.22-0.90)/0.02$	16	Stackelberg equilibrium
2.06	$(2.06-0.90)/0.02$	58	Capacity limit

Table 2 shows that farmer supply increases with the procurement price and reaches the harvesting capacity at $p = 2.06$. At the equilibrium price $p^* = 1.22$, supply is $q^* = 16$, confirming that the capacity constraint is non-binding. Figure 2 illustrates this piecewise supply response.

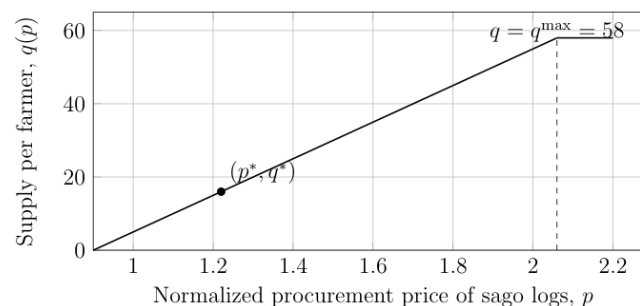


Figure 1. Farmers' supply reaction function with the harvesting capacity constraint

Numerical illustration of the processing industry's profit

To illustrate how the processing industry's profit varies with different procurement prices, Table 3 presents numerical calculations based on Equation (7) where $A = 1250$, $\alpha = 0.18$, $P = 13$, $c = 0.9$, and $d = 0.002$.

Tabel 3. Processing industry profit under different procurement prices

Procurement price p	Total supply Q	Industry profit π_L	Remarks
1.10	250	247.5	Within reference range
1.20	375	286.9	Profit increases
1.22	400	288.0	Maximum profit (at p^*)
1.30	500	270.0	Profit begin to declines
1.40	625	196.9	Profit declines

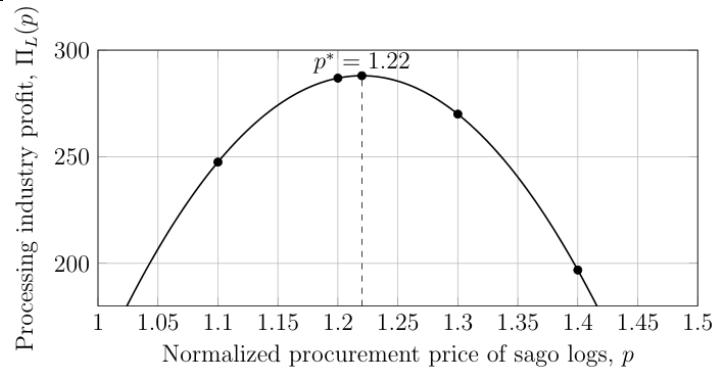

Figure 3. Processing industry's profit as a function of the procurement price

Figure 3 shows that the processing industry's profit is strictly concave in the procurement price, consistent with the analytical second-order condition. Profit initially increases as a higher procurement price induces greater farmer supply and increases processing volume. Beyond the optimal price, the additional procurement and processing costs outweigh the associated revenue gains. The maximum profit is therefore attained at $p^* = 1.22$, corresponding to an industry profit of 288.00 in normalized monetary units.

The numerical illustration shows that the proposed model generates an equilibrium procurement price of 1.22 in normalized monetary units, equivalent to approximately IDR 61,000 per sago log. This value lies within the reported reference procurement price range for good-quality sago logs. The result indicates that the processing industry's procurement decision must balance the incentive provided to farmers with the industry's procurement and processing costs. This finding is relevant to the upstream sago supply chain, where farmers have been reported to have limited bargaining power and where processing industries play an important role in determining procurement conditions (Anwar, 2023; Riza *et al.*, 2017). The equilibrium price should therefore be interpreted as an analytical benchmark rather than as a direct prediction of the observed market price.

The equilibrium procurement price induces an individual farmer supply of 16 logs per month, below the benchmark capacity of 58 logs per farmer per month. Aggregate supply reaches 400 logs per month, well below the benchmark capacity of approximately 1,450 logs for 25 farmers, indicating that the capacity constraint is non-

binding under the selected parameters. The cost parameters also have clear economic roles namely c primarily affects the equilibrium procurement price, while k and d influence the supply response by increasing harvesting and processing costs, respectively. These relationships highlight the role of procurement incentives and production costs in shaping farmer participation and supply, consistent with previous studies on raw material availability and farmer incentives in the upstream sago supply chain (Elida *et al.*, 2021; Trisia *et al.*, 2021).

The processing industry's profit reaches its maximum at the equilibrium procurement price, reflecting a trade-off between increasing raw material supply and increasing procurement and processing costs. The numerical results also show that the processing industry obtains a higher aggregate profit than the combined profit of the farmers under the assumed buyer-led structure. This result provides an analytical perspective on previous empirical findings regarding the bargaining position of sago farmers and the important role of processing industries in procurement transactions (Anwar, 2023; Riza *et al.*, 2017). Overall, the proposed model complements previous sago supply-chain studies by explicitly representing procurement pricing as a strategic interaction between the processing industry and farmers, while providing closed-form equilibrium solutions for procurement price and supply decisions.

D. CONCLUSIONS

This study developed a baseline analytical Stackelberg game model to examine procurement pricing and farmers' supply decisions in the upstream sago agro-industry supply chain. The processing industry acts as the leader, determining the procurement price, while farmers respond through their supply decisions. The model provides closed-form solutions for the equilibrium procurement price and farmers' supply response. The numerical illustration yields an interior equilibrium procurement price of 1.22 in normalized monetary units, equivalent to approximately IDR 61,000 per sago log. At this price, each farmer supplies 16 logs per month, resulting in an aggregate supply of 400 logs per month, below the benchmark harvesting capacity of 58 log per farmer per month. Both farmers and the processing industry obtain positive profits, with the processing industry obtaining higher aggregate profit under the assumed buyer-led structure. The model provides a tractable baseline for analyzing procurement pricing and farmer supply decisions. The model assumes homogeneous farmers, an exogenous selling price, deterministic conditions, a single-period framework, and an interior equilibrium. These assumptions provide directions for future extensions involving farmer heterogeneity, uncertainty, competing buyers, dynamic decisions, and coordination mechanisms.

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