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From ambiguity to transparency: Blockchain-enabled origin traceability for premium agricultural product

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ABSTRACT

Rising living standards have turned premium and origin-specific agricultural produce into a symbol of lifestyle and social prestige, but limited consumer expertise leaves room for adulteration by mixing products from non-core origins with core products without supply chain traceability. Achieving transparency and traceability in the agricultural supply chain has long been a challenge until blockchain technology emerged as a credible, immutable solution. This study explores how blockchain-enabled origin traceability alters premium agricultural retail by affecting the farmer's choice between the honest origin differentiating and opportunistic blending. We analyze the farmer's strategic decisions by considering consumers' heterogeneity stemming from their ability to discern the true origin without a blockchain traceability system, and conduct a parallel analysis after its implementation. We find that without blockchain, the farmer always favors blending to increase profits and, even under the differentiating strategy, sets an overpriced retail price to exploit the high willingness to pay. With blockchain, transparency empowers the farmer to credibly differentiate products and align profits with honest operations. Finally, we present a real-world case study demonstrating how blockchain supports both profitability and market integrity. This research underscores that, when properly implemented, blockchain-enabled origin traceability aligns economic incentives with the honest retailing strategy, bolsters consumer trust, and upholds integrity throughout the agricultural supply chain.

1. Introduction

1.1. Background and motivation

The agricultural sector plays a vital role in the global economy by providing essential goods and sustaining rural livelihoods. Nowadays, as living standards rise, consumers are no longer purchasing agricultural products solely out of necessity; they seek products that offer superior taste, health benefits, and specified origin which demonstrate the social prestige and lifestyle. For instance, the demand for premium tea, organic produce, vintage wine, and prime beef steak has surged, driven by consumers' desire for high quality, which signifies status and conscientious living. Consumers are willing to pay a premium for rigorous standards of original authenticity and quality.

Premium grocery chains emphasize exclusivity with products sourced from renowned regions. For instance, wines from Bordeaux, cheese from France's Normandy region, and Longjing tea from Hangzhou, China, are marketed not only for their taste but also for the

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Table 1
Applications of blockchain in premium agricultural supply chain.

Product Type	Platform	Brief Description
Cheese	p-Chips	The Parmigiano Reggiano Consortium embeds micro-transponder "p-Chips" in cheese rinds, creating a blockchain-registered digital twin for each wheel to guarantee authenticity and provenance
Coffee beans	IBM Food Trust	Nestlé has used IBM Food Trust to trace coffee beans via QR codes, logging farmer IDs, harvest dates, and processing steps since 2017
Grape	GrapeNet	GrapeNet is an blockchain-based traceability software system for monitoring fresh grapes exported from India to the European Union
Hairy carbs	ECMI	Researchers develop a blockchain-IoT traceability system (using Enhanced Cuckoo Merkle Index (ECMI)) that logs breeding, disease control, and logistics-ensuring data security and consumer trust.
Livestock	NLIS	Australia has its National Livestock Identification System (NLIS) to keep track of livestock from birth to slaughterhouse
Tuna	Bumblebee	It tracks tuna from catch to can on a blockchain platform, logging vessel, catch-date, and processing information in an immutable ledger

cultural heritage they represent from their origins. These products are often featured prominently in stores, appealing to consumers who associate these geographic indicators with superior quality or flavor. As these examples illustrate, the preference for premium labels reflects a growing market segment that values not just the functional aspects of food but the story, scarcity, and prestige behind it. However, ensuring that these high standards are maintained and verified throughout the supply chain poses significant challenges. Farmers and producers often face incentives misaligned with transparency and quality, particularly when deliberate adulteration, such as mixing or blending, can boost profits (U.S. Food and Drug Administration, 2024). Speculative practices, such as blending, adulterate lower-quality products with premium goods to save on costs and command higher prices. For example, a tea producer from a non-core planting region might blend their products with tea from renowned core areas, similar to how manufacturers dilute high-value olive oil with cheaper vegetable oils or adulterate honey with corn syrup. These dishonest practices deceive consumers and poses long-term risks to brand reputation and consumer health.

Blending non-origin products with genuine premium goods is a rampant form of speculation, exploiting markets where consumer trust relies on superficial labels and vague promises rather than concrete traceability assessments. In the absence of comprehensive verification systems, these fraudulent practices persist, wreaking havoc on the integrity of premium markets and eroding the consumers' utility by selling the premium agricultural produce with incompatible price. Unlike other attributes, such as organic and gluten-free designations, which can be definitively identified through chemical and spectral analyses, it is exceedingly difficult for consumers to detect minor disparities in ingredients between an authentic original produce and its adulterated counterpart. Thus, it becomes paramount in ensuring the verifiable origins of these products.

Blockchain's decentralized and immutable ledger have already enabled applications that facilitate supply chain financing by providing transparent transaction data, enhancing privacy protection through secure data access controls, and bolstering anti-counterfeiting measures by ensuring product authenticity. The emergence of blockchain technology offers a promising solution to adulteration challenges in the agricultural sector by embedding traceability and transparency into the stages of supply chains. Without blockchain adoption, the farmer may be tempted to act dishonestly by blending products from non-core regions with premium goods, misrepresenting their quality to boost profits. This approach exploits the lack of verifiable quality information and takes advantage of consumer trust. However, blockchain traceability fundamentally changes this dynamic by enforcing transparency across the supply chain. With every step recorded-from the origin of raw produces to the final sale-it becomes significantly more difficult to disguise lower-quality products as premium. This shift toward transparency can effectively prevent dishonest practices like blending and encourage the farmer to pursue quality differentiation. By providing verifiable proof of the origin, blockchain technology enables the farmer to command higher prices for genuinely superior products, creating an environment where honesty is economically rewarded. As consumers become more willing to pay a real premium for products they can trust, the farmer who adopts blockchain gains stronger incentives to maintain high standards and build a reputation for its origin. Thus, blockchain acts beyond as a tool for traceability, and also as a mechanism that aligns profitability with honest business operations, driving the market toward greater integrity. Table 1 below presents several real-world examples of blockchain adoption in the premium agricultural sector.

1.2. Research questions and contributions

To facilitate our analysis of how the blockchain-enabled traceability system influence farmers' retail strategies in agricultural supply chain, we address the following research questions. Q1. What does the current market landscape look like? Specifically, what are the farmer's optimal pricing, quality, and demand-fulfillment decisions under each retailing strategy without the blockchain traceability system? Q2. Under what conditions does the farmer resort to the dishonest blending strategy without blockchain, and to what extent does the consumer suffer from the willingness-to-pay caused by origin ambiguity under each retailing strategy? Q3. How does the blockchain traceability system impact the farmer's profitability? Does it prompt the honesty? What is the relationship between the yield scarcity and market supervision when the blockchain is adopted?

To address these questions, this paper employs a utility model to analyze the economic effects of implementing a blockchain traceability system within agricultural supply chain. We formulate three retailing strategies, including the blending strategy, the differentiating strategy, and the differentiating strategy with blockchain. The farmer cannot apply the blending strategy once they adopt the blockchain, since the traceability system always discloses the true origin of the product. We find that the price under the blending strategy can exceed that of premium products under the differentiating strategy without blockchain traceability, particularly when the cost of blending the non-core products is high. Additionally, under the differentiating strategy, the farmer strategically sets retail prices to ease competition between core and non-core products, while imposing a premium that exceeds the linear increment in quality, indicating an intent to capture extra margins from consumers beyond the product's intrinsic value. Furthermore, our analysis indicates that without a blockchain traceability system, the farmer will always opt for blending, allowing them to manipulate prices and increase margins by concealing true product origin. This dishonest behavior ultimately reduces consumer reachability, which is undesirable from a market perspective.

Adopting a blockchain traceability system eliminates consumer heterogeneity on the origin ambiguity, inducing alignment among consumer's actions when desired products are available. Additionally, blockchain incentivizes the farmer to shift from blending to differentiating strategy, promoting business integrity by coordinating honest business operations with financial incentives. Our analysis presents that when the quality differences between core and non-core products are recognizable, the farmer obtains more profits under the differentiating strategy. Interestingly, an increase in the purchasing cost of non-core products may lead to the opposite outcome, where the farmer profits more through blending. This occurs because, with perfect quality disclose, the farmer cannot further raise retail prices despite higher costs. However, by concealing true quality, the blending strategy can raise retail prices to offset potential profit losses. Beyond the theoretical analysis, we further present a real-world case study from a tea trade market in Shandong Province China, where products from both core and non-core regions are prevalent. We examine how blockchain technology adoption impacts the farmer's strategic decisions and encourages honest practices, and numerically verifying that the increasing market supervision or transaction fees related to blockchain traceability may prompt the farmer to abandon the differentiation strategy and revert to blending.

1.3. Paper organization and structure

The rest of the paper is organized as follows. Section 2 reviews the related literature and highlights how our study differs from the existing research. Section 3 derives and compares the strategic decisions for both the blending and differentiating strategies without the blockchain traceability. Section 4 presents the optimal pricing strategy and profit under the differentiating strategy with the blockchain traceability adoption. Section 5 offers a comparative analysis of demand, pricing, and optimal retailing strategies. Section 6 includes a case study illustrating the real-world application of blockchain traceability. Finally, Section 7 concludes the study with key managerial insights.

2. Literature review

We review the literature in three separate streams pertinent to our study, namely research on (a) blockchain technology in anti-counterfeiting, (b) innovative technology in agricultural supply chain, and (c) product line design and market segmentation.

2.1. Blockchain technology in anti-counterfeiting

There has been extensive research on the application and impact of blockchain technology in supply chain management, with (Dutta et al., 2020) provide a comprehensive review. Blockchain technology provides firms and consumers with transparent and traceable data, as each transaction is securely recorded and product information remains immutable (Dong et al., 2022a). Babich and Hilary (2020) identify three key aspects of the integration of blockchain in operations management: (*i*) information, (*ii*) automation, and (*iii*) tokenization. The existing literature has thoroughly examined blockchain's role in supply chain finance (Dong et al., 2022b; Wang and Xu, 2022), inventory management (Xiong et al., 2025), sustainability (Cao and Shen, 2022), and remanufacturing (Niu et al., 2022; Wang et al., 2025), by leveraging its inherent transparency. Among others, blockchain technology, due to its immutability, transparency, and decentralized properties, has been widely applied in the area of counterfeiting prevention (Shen et al., 2022). Li et al. (2021) show how blockchain adoption influences channel strategies to combat counterfeits and improve social welfare, especially under high risk aversion or limited consumer expertise. Zhou et al. (2022) shows that the anti-counterfeiting can hurt the platform, manufacturer, and the consumer when either the product's value or the proportion of fakes is sufficiently low. Similarly, Pun et al. (2021) examine the impact of adopting blockchain technology on deceptive counterfeiting. Shen et al. (2021) examine how quality inspection and blockchain adoption combat counterfeit masks during COVID-19, revealing that blockchain can incentivize authentic sellers to improve quality and reduce health risks, especially when infection rates are high. Both (Shen et al., 2020) and (Pun et al., 2025) examine blockchain in secondhand markets, with the former highlighting its role in enhancing transparency and enabling win-win-win outcomes, especially for low-uniqueness products; and the latter revealing that it may instead harm manufacturers, resellers, and consumers. Our study explores how the farmer can leverage the blockchain-enabled origin transparency to inform operational decisions, specifically pricing and ordering, and examines how this transparency impacts profitability.

2.2. Innovative technology in agricultural supply chain

Although the agricultural supply chain is a well-established topic, its importance has driven a continuous emergence of new research. Within the blockchain context, Keskin et al. (2024) study a newsvendor model with freshness-sensitive demand and show how blockchain improves retailer profits and reduces food waste. Dong et al. (2022a) model a three-tier supply chain to show that while blockchain-enabled traceability can reduce food waste and contamination risks, it may make the deep-tier suppliers worse off with strategic pricing and reduced upstream effort. Liu et al. (2022) model blockchain adoption in imported fresh food supply chains during COVID-19 and show its profitability hinges on alleviating consumer safety concerns and the risk attitudes of manufacturers, retailers, and consumers. Cao et al. (2022) demonstrate that a blockchain-based platform can improve production, trust, and sustainability in agricultural supply chains, though its value diminishes in highly credible environments and may not always benefit all participants. Similar to blockchain technology, RFID also has the specialty in enabling the traceability, and (Alfian et al., 2020) provide a comprehensive analysis of recent advances that integrate RFID sensors and and Internet-of-Things (IoTs) with machine learning to enhance traceability in perishable food supply chains through real-time monitoring of product movement, temperature, and humidity. While RFID relies on physical sensors and IoTs to track the flow of agricultural products, blockchain presents the convenience by enhancing information flow with immutability and decentralization features. By developing a multi-period optimization model, Jahantab et al. (2023) help farmers transition to organic farming while minimizing income shortfalls, demonstrating that gradual conversion with optimized crop rotation outperforms conventional practices like monoculture. Two adjacent researches examine the effects of agricultural subsidies on farm output, income distribution, and welfare, with one focusing on subsidy types and efficiency (Fan et al., 2023), and the other on income inequality and total income (Tang et al., 2023). Akkaya et al. (2020) analyze how taxes and subsidies influence farmers' adoption of innovative production methods under uncertainty, showing that while subsidies enhance social welfare, taxes better promote experimentation, and offering policy guidance based on a case study of organic egg production in Denmark. Ayvaz-Çavdaroğlu et al. (2021) illustrate that open-market-based payments lead to farmer underinvestment in quality, while alternative policies, especially with crop insurance, can boost profits, as evidenced in Turkey's olive oil industry. Xu et al. (2025) investigate the impact of blockchain adoption in agricultural supply chains on quality improvement within live streaming contexts, revealing that introducing both the live streaming channel and the influencer can be detrimental to the farmer when they are less efficient. Similar to our work, they find that blockchain enhances information transparency and increases purchase likelihood. In contrast, whereas (Xu et al., 2025) focus on quality improvements enabled by blockchain transparency, our study emphasizes the role of product origin traceability in shaping consumer trust and promoting the honest practices. Differentiating from the existing studies, we first examine how dishonest businesses strategically incorporate the non-core products to profit without utilizing blockchain technology. Furthermore, we investigate the impact of blockchain traceability system on the pricing of agricultural products, and among the first to introduce the origin as a quality metrics in the existing literature, revealing how technology adoption aligns with the interests of agricultural producers and promotes integrity.

2.3. Product line design and market segmentation

Our study also falls into the research of product line design and market segmentation. Zhao et al. (2025) study the firm's price, quality, and product line decisions in the environmental supply chain with the presence of socially responsible consumers. Dong et al. (2023b) show that responsive pricing improves value, but its effects on orders and diversification hinge on costs, reliability, and portfolio mix with yield uncertainty. Jiang et al. (2022) investigate how capital-constrained, service-oriented manufacturers leverage crowdfunding to optimize quality and pricing decisions tailored to different customer types. He et al. (2023) studies the optimal pricing strategy of product line design for green and non-green products with blockchain technology. Berbeglia et al. (2021) investigate optimal ranking strategies in a trial-offer marketplace with diverse consumer preferences and social influences, demonstrating that market segmentation can significantly enhance long-term purchase outcomes despite the complexity of the ranking problem. Cao et al. (2023) study the optimal contract design for a national brand manufacturer under store brand private information. Geng et al. (2022a) study the impacts of social interactions on firms' quality differentiation, pricing decisions, and profit performance by considering the market-expansion effect and value-enhancement effect. Dong et al. (2021) examines how 3D printing's unique attributes-design freedom, quality distinction, and natural flexibility-affect a firm's optimal product assortment. We differentiate from existing studies by incorporating the product origin as a distinct quality metric to examine the blockchain's influence on the farmer's strategic product line presentation and curbs dishonest blending by aligning economic incentives with honest operations. Finally, we delineate research gaps in Table 2 by comparing our work with related literature.

3. Retailing strategies without blockchain

This section examines the current two retailing strategies without blockchain traceability: the blending strategy (denoted by subscript B), which offers a single product created by strategic mixing, and the differentiation strategy (denoted by subscript D), which discloses quality and markets the two product types separately. For the core product (denoted by the subscript C), we generally refer to the agricultural product that is cultivated and processed within a specific geographic region, presenting unique qualities attributed to the area's natural environment and traditional practices. Examples include China's Yangcheng Lake hairy crabs and Italy's Prosciutto di Parma (Parma Ham). And the non-core product (denoted by subscript N), we generally refer to agricultural products that are similar but produced outside the traditional or designated regions. Although they might be comparable in quality and functionality, the lack specific geographical indications often leads to lower brand recognition and reduced market value for the non-core product. Under the blending strategy, the farmer mixes core and non-core products into a single offering, then dishonestly markets it as the core product by exploiting origin ambiguity. While under the differentiation strategy, the farmer transparently discloses product quality and markets the core and non-core products separately. We outline the key notations used throughout the paper Table 3.

Table 2
Positioning of this study in literature.

Study	Product Type		Operational Attribution		Strategic Decisions		
	Single Product	Multi-products	Traceability Adoption	Integrity Consideration	Price	Quality	Quantity
Alfian et al. (2020)		✓	✓			✓	✓
Ayvaz-Çavdaroğlu et al. (2021)	✓				✓	✓	
Li et al. (2021)	✓		✓		✓		
Cao and Shen (2022)		✓	✓	✓	✓		✓
Jiang et al. (2022)	✓	✓			✓	✓	
Liu et al. (2022)	✓		✓		✓		
Shen et al. (2022)		✓	✓		✓	✓	
Zhou et al. (2022)	✓				✓		✓
Chen and Duan (2023)	✓			✓	✓		✓
Dong et al. (2023a)	✓		✓	✓	✓		✓
Keskin et al. (2024)	✓		✓			✓	✓
Kazaz et al. (2025)	✓	✓			✓	✓	✓
Pun et al. (2025)	✓		✓		✓		✓
Xu et al. (2025)	✓		✓		✓	✓	✓
Zhao et al. (2025)	✓	✓		✓	✓	✓	
This study	✓	✓	✓	✓	✓	✓	✓

Table 3
Key notations.

Category	Expression	Description
Decisions	p	retail price
	Q	purchasing quantity of the non-core product
	z	proportion of the core product in blending strategy
Randomness	v	willingness-to-pay with origin ambiguity, $v \in U[0,1]$
Parameters	θ	consumer's perceived quality of the non-core product
	y	yield of the non-core product
	c	purchasing cost of the non-core product
	D	market demand
	b	blockchain adoption cost
	r	reputation cost
Derivatives	π	farmer's profit
	θ_B	true quality of the blended product
	U	consumer utility

3.1. *The blending strategy*

Consumers perceive a quality difference between the core product and the non-core product. In practice, consumers vary in their ability to discern the true quality of the blended product. For example, in coffee blends combining premium Ethiopian beans with lower-grade beans, experts detect subtle flavor nuances that most consumers miss (Perfect Daily Grind, 2020). We represent the consumer's willingness to pay resulting from this ambiguity as v, and assuming that consumer heterogeneity is uniformly distributed over $[0,1]$. The perceived quality of the core product is normalized to 1, while the perceived quality of the non-core product is denoted by θ, where $\theta \in (0,1)$, reflecting its lower value compared to the core product.

Under the blending strategy, where the core product is yield y, the farmer sets the total supply Q_B, of which a fraction $z \in (0,1]$ represents the core product. For simplicity, the market potential is normalized to 1, implying that the heterogeneous consumers with $v \in [0,1]$ can purchase at most one unit product from the market. Due to the scarcity of the core product, we assume the total yield, y, does not exceed half of the market size, i.e., $y \in \left(0, \frac{\theta}{1+\theta}\right]$, and can always be fully absorbed by the market if solely sold. This assumption ensures the total blended supply remains within the market size, as the farmer does not have the motivation to make the blended quantity exceed the market potential. And we refer readers to Appendix B for a detailed explanation, where we justify the assumption both theoretically and empirically. In addition, since the farmer cultivates the core product in-house, and independently as well as identically across different retailing strategies, we omit the corresponding planting cost without the loss of generality. To obtain the non-core product in the quantity of $Q_B - y$, the farmer purchases from the outside market at unit cost c.

Therefore, the true quality of the blended agricultural product is a weighted mix of the core and non-core components, given by $\theta_B = (1-z)\theta + z \cdot 1$. When faced with the farmer's retail price, p_B, the consumer has the option to either purchase or refrain from purchasing. The utility of a consumer with willingness to pay, under origin ambiguity v, is expressed as $U_B = \theta_B v - p_B$, which is commonly found in previous study (Kazaz et al., 2025). Therefore, for a given price p_B and core proportion z, the demand for the

Table 4
Impacts of increasing parameter values under blending strategy.

Parameter	p_B^*	Q_B^*	z^*	π_B^*
θ	$\downarrow - \uparrow$	$\uparrow$	$\downarrow$	$\uparrow$
c	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$
y	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$

Note: $\uparrow$ = increase; $\downarrow$ = decrease; $\downarrow - \uparrow$ = decrease, then increase. Same as tables after.

blended product can be expressed as:

$$D_B(p_B, z) = \Pr\left[U_B > 0\right] = 1 - \frac{p_B}{\theta_B(z)}. \tag{1}$$

The farmer aims to maximize profit by determining the optimal retail price, p_B^*, total supply quantity, Q_B^*, and optimal blending proportion, z^*. Therefore, the farmer's problem is:

$$\max_{p_B, Q_B, z} \pi_B\left(p_B, Q_B, z\right) = p_B D_B(p_B, z) - c\left(Q_B - y\right), \tag{2}$$

$$\text{s.t.} \quad Q_B = \frac{y}{z}, \tag{3}$$

$$Q_B = D_B(p_B, z). \tag{4}$$

Eq. (2) represents the farmer's profit as the revenue generated from demand minus the cost of acquiring the non-core product from the market. Eq. (3) further indicates that the total supply quantity is determined by the core product yield divided by its proportion in the blend. Additionally, since the market potential is normalized to 1, the condition $\frac{y}{z} \leq 1$ must hold, which implies $y \leq z$. This reflects the practical constraint that the core product's proportion in the blend cannot be too low relative to the total quantity offered, as an excessively diluted blend would make the lower quality more apparent to consumers. A blend dominated by the non-core product would be difficult to sell due to reduced perceived quality. Consequently, the blending strategy can only support a limited expansion beyond the core yield, rather than allowing arbitrarily large gains.

Since the farmer simultaneously decides the retail price and the quantity of non-core product to purchase—effectively determining Q_B—any unsold quantity yields no profit. As a result, the farmer always carefully balances the price and the quantity purchased to ensure that the total supply aligns precisely with the demand implied by the chosen price (Eq. (4)). To ensure that the optimal blending proportion, z^*, remains within the feasible range of 0 to 1, we propose a reasonable upper limit for purchasing cost of the non-core product, given by $c < \theta - (1+\theta)y$. The following proposition provides the expressions for the optimal retail price p_B^*, optimal supply quantity Q_B^*, and optimal blending proportion z^* under the blending strategy.

Proposition 1. *Given $c < \theta - (1+\theta)y$,*

1. *The farmer's optimal retail price p_B^*, supply quantity Q_B^*, blending proportion z^*, and the profit π_B^*, are expressed as the follows:*

$$\left\{p_B^*, Q_B^*, z^*, \pi_B^*\right\} = \left\{ \frac{(\theta + y - \theta y)^2 - c^2}{2[(1+y)\theta - y - c]}, \frac{\theta - c - (1-\theta)y}{2\theta}, \frac{2\theta y}{\theta - c - (1-\theta)y}, \frac{(c + y + \theta - \theta y)^2}{4\theta} - c(1-y) \right\};$$

2. *The impact of key parameters is summarized in Table 4.*

Proposition 1 characterizes the optimal pricing, supply, and blending decisions under the blending strategy. As the perceived quality of the non-core product, denoted by θ, increases, the farmer's profit rises due to the concave increase in demand driven by enhanced consumer-perceived value. Given the limited yield of the core product, the farmer must supplement the supply with market-purchased non-core product to satisfy rising demand, which consequently lowers the proportion of core product in the final blend. Holding other parameters constant, a moderate increase in θ allows the farmer to achieve the same overall blended quality θ_B at a lower cost. This cost saving, coupled with a sharp rise in demand, enables the farmer to adopt a quantity-driven strategy by reducing the retail price p_B to maximize profit. However, once θ becomes sufficiently high, the concavity of the demand function tempers the marginal growth in demand. Nevertheless, the large demand volume and elevated consumer valuation sustain the product's attractiveness, allowing the farmer to justify and implement a higher retail price. Here, we observe the farmer's strategic pricing behavior: initially lowering the retail price to stimulate rapid demand growth when when products are distinct, and later raising the price when consumers' recognition becomes large.

As the unit cost of the non-core product increases, the overall blending cost rises accordingly. To preserve profitability, the farmer responds by raising the retail price and reducing the quantity of non-core product purchased, thereby mitigating the additional cost burden. This price adjustment, however, dampens consumer demand and results in lower profit. To counterbalance the rising cost of the non-core product, the farmer increases the blending proportion of the core product, aiming to limit excessive expenditure while maintaining the target blended quality θ_B. This strategy serves to alleviate the decline in demand caused by the increased retail price.

Both the retail price and the proportion of core product increase as the yield of core product rises. The increase in retail price alongside rising yield may appear counterintuitive at first. However, it stems from the enhanced overall quantity and quality of the blended product, which justifies a higher retail price. This improves the overall perceived quality of the blended product, θ_B,

Table 5
Impacts of increasing parameter values under differentiating strategy.

Parameter	p_C^*	p_N^*	D_N^*	π_D^*
θ	↓	↑	↑	↓
c	↑	↑	↓	↑
y	↓	↓	N/A	↑

though the demand diminishes due to the more significant impact of the increased price. Notably, there is an implicit substitution effect between core-product and non-core product, even within the farmer's decision-making process. Under the assumption that $c < \theta - (1+\theta)y$, which ensures that the proportion of the core product remains below 1, we observe that an increase in either the cost of the non-core product or the yield of the core product reduces the farmer's reliance on purchasing non-core input. This suggests that, despite exhibiting opportunistic behavior, the farmer remains motivated to enhance the overall quality of the blended product (θ_B) in order to maximize profit. This behavior, in turn, supports our assumption that $y \le z$, indicating that the farmer does care about maintaining product quality, rather than merely minimizing costs at the expense of consumer value. Ultimately, the farmer seeks to strike a balance between quality and cost to optimize returns, even when the strategy involves blending lower-quality components.

3.2. The differentiating strategy

Under the differentiating strategy, the farmer offers two distinct choices by separating the core product and the non-core product, each with dedicated pricing. Consumers have three options: they can purchase the core product, purchase non-core product, or choose not to purchase at all. The retail prices of core product and non-core product are denoted by p_C and p_N, respectively. To incentivize consumers to purchase the non-core product, the farmer always sets $p_N < p_C$ (Grewal et al., 2019). The consumer's utility from purchasing the core product is given by $U_C = 1 \cdot v - p_C$, while the utility from purchasing the non-core product is $U_N = \theta v - p_N$. Similar to the blending strategy, the farmer must source the additional quantity of the non-core product from an external supplier at a unit cost of c. It is assumed that $\theta > c$, as otherwise the farmer would have no incentive to purchase the non-core product from the outside market. Consumers choose either the core product or the non-core product based on which provides the highest utility, and will opt not to purchase if neither product generates a positive utility, where Lemma 1 provides the detail.

Lemma 1. *The demand for the core product and the non-core product is expressed as:*

$$D_C(p_C, p_N) = \Pr\left[U_C > \max\{U_N, 0\}\right] = 1 - \frac{p_C - p_N}{1-\theta}, \tag{5}$$

$$D_N(p_C, p_N) = \Pr\left[U_N > \max\{U_C, 0\}\right] = \frac{\theta p_C - p_N}{\theta(1-\theta)}. \tag{6}$$

From Lemma 1, the term $(p_C - p_N)/(1-\theta)$ represents the threshold where the additional price charged for the core product matches the perceived quality difference between the two products. And consumers with a willingness to pay the premium fall between this boundary and 1. The influence of θ demonstrates how perceived quality impacts demand: as the quality of the non-core product becomes more comparable to that of the core product, fewer consumers are willing to pay the premium for the core product. Consequently, D_C decreases as θ increases and increases as p_N rises. Intuitively, when consumers' perceived quality of the non-core product improves-through stronger marketing or branding-they substitute away from the core product, reducing D_C. Conversely, a higher non-core price p_N makes the non-core product less attractive, so D_C rises. Similarly, D_N increases with both the core price p_C and the perceived quality θ. And a higher p_C also allows room for a higher non-core price. Now, we formulate the farmer's problem as the following:

$$\max_{p_C, p_N} \pi_D(p_C, p_N) = p_C D_C(p_C, p_N) + (p_N - c) D_N(p_C, p_N), \tag{7}$$

$$\text{s.t.} \quad D_C(p_C, p_N) \le y, \tag{8}$$

$$D_N(p_C, p_N) \ge 0. \tag{9}$$

Eq. (7) defines the farmer's profit as the sum of the profit from selling the core product and the profit from selling the non-core product. The farmer can sell no more core products than the yield (see Eq. (8)), while Eq. (9) ensures that the demand for the non-core product remains non-negative. We present the farmer's optimal pricing strategy in the following proposition:

Proposition 2.

1. *The farmer's optimal retail prices p_C^* and p_N^*, market demand D_N^*, and profit π_D^*, are expressed as the follows:*

$$\{p_C^*, p_N^*, D_N^*, \pi_D^*\} = \left\{ \frac{2+c-2y-\theta}{2}, \frac{c+\theta-2\theta y}{2}, \frac{\theta-c}{2\theta}, (1-y)y - \frac{(\theta-c)^2}{4\theta} \right\};$$

2. *The impact of key parameters is summarized in Table 5.*

From Proposition 2, an increase in the perceived value of the non-core product, represented by θ, leads to a higher optimal retail price for the non-core product (p_N^*) and a lower optimal retail price for the core product (p_C^*). Moreover, the increase in θ further drives up demand for the non-core product but reducing overall profit because selling the core product has become relatively less competitive. This finding aligns with insights from the blending strategy, where the substitution effect reduces demand for the core product as θ rises. It reveals that, under the differentiating strategy, the farmer's profit heavily depends on how much the core product can be priced, rather than that of the non-core product, which triggers us to exam whether the price of the core product is at a premium. Additionally, when the cost of purchasing increases, which would intuitively hurt profits, the farmer mitigates this impact by raising p_N^* to offset the additional expense. This adjustment also lifts p_C^* as well, ultimately leading to an overall profit rise. Therefore, although the increased purchasing cost of the non-core product reduces demand, it also leverages the farmer an excuse to pursue a larger unit margin, and finally increases the overall profit.

An increase in the yield boosts the supply of the core product, reducing its scarcity and leading to lower retail prices. The reduction in p_C^* also depresses the retail price for the non-core product. However, under the differentiation strategy, demand for the non-core product is independent of core product supply. The farmer therefore segments consumers into two groups and focuses solely on adjusting the non-core price, holding its sales quantity fixed. Although both retail prices decrease, the increased sales volume justifies that profit continues to rise. The following corollary further illustrates the farmer's inherent pricing strategy under differentiation.

Corollary 1. *Under the differentiating strategy, given $\theta > c$, the ratio of the optimal retail prices is greater than the ratio of the quality levels between the core product and the non-core product, i.e., $p_C^*/p_N^* > 1/\theta$.*

Corollary 1 demonstrates that the farmer consistently prices the core product and the non-core product in a differentiated manner, setting the price of the core product higher than the corresponding quality gap. Setting the differentiated retailing prices between the core product and the non-core product that exceeds the actual quality difference is a strategic way to maximize potential profit. By pricing the core product at a premium, the farmer extracts more revenue from consumers' willingness to pay for the high quality, resulting in greater profit margins. By effectively segmenting the market, the farmer captures the maximum willingness to pay from both high-end and price-sensitive consumers, reducing demand overlap and maintaining the desired margins across both product categories. Such an approach not only increases revenue from premium buyers but also avoids product cannibalization and optimizes profits across the entire customer base.

3.3. Comparison of the strategies without the blockchain traceability system

In this subsection, we discuss the optimal pricing and retailing strategies without the blockchain traceability system.

3.3.1. Pricing strategies comparison

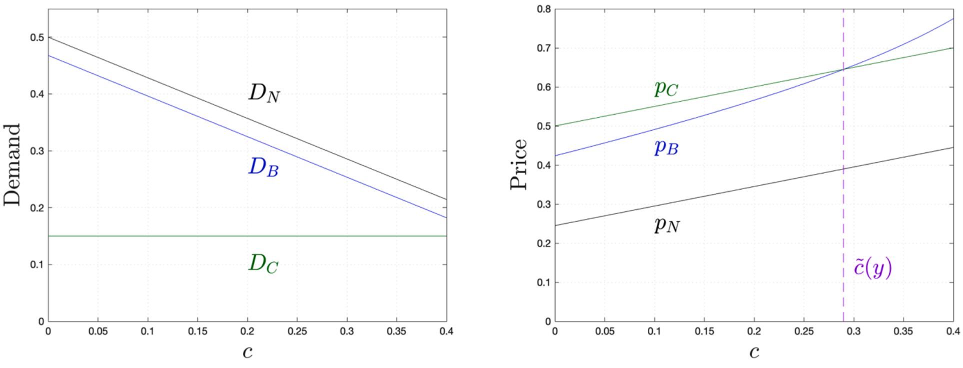
Having derived the optimal pricing strategies for both the core product and the non-core product, the following proposition outlines the specific pricing relationships under the two retail formats.

Proposition 3.

1. *The retail price under the blending strategy is always higher than the retail price of the non-core product under the differentiating strategy, i.e., $p_B^* > p_N^*$;*
2. *There exists a unique threshold $\tilde{c}(y)$ such that when $c > \tilde{c}(y)$, $p_B^* > p_C^*$; otherwise, $p_B^* < p_C^*$. Note that $\tilde{c}(y)$ decreases as y increases;*
3. *The ranking of price-determined demand for the three products is $D_N^* > D_B^* > D_C^*$.*

We can conclude that $p_B^* > p_N^*$ always holds as the perceived quality of the blended product, θ_B, is higher than the perceived quality of the non-core agricultural product, θ, under the differentiating strategy. Consumers are willing to pay more for the higher perceived quality. Additionally, based on the derivations in Propositions 1 and 2, $D_N^* > D_B^*$ is guaranteed mathematically by $(1-\theta)y > 0$, indicating that the blending strategy cannot both command a higher retail price and satisfy greater demand than the non-core product. Furthermore, we observe that $D_B^* > D_C^*$, explaining the farmer's intuition to strategically exploit the ambiguity in absence of the blockchain and command the blended product a higher demand beyond the scarce core-product. Fig. 1a provides a numerical example of how the consumer demand evolves with regard to c.

Specifically, although the integrated perceived quality of the blended product, θ_B, is lower than that of the core product under the differentiating strategy, the retail price can still be higher when the unit purchasing cost of the non-core product, $c \in (\tilde{c}(y), \theta - (1+\theta)y)$. The main rationale lies in the differences of pricing structures. Under the differentiating strategy, the farmer must balance and adjust p_C^* and p_N^* to maximize profit while also ensuring that all purchased non-core product is sold. In contrast, the blending strategy allows the farmer to sell the blended product in a monopolistic manner, with no internal competition between products. Specifically, at the micro level, the farmer prices p_C^* and p_N^* linearly based on a cost-oriented approach under the differentiating strategy. That is, when the cost of the non-core product increases, the farmer adds a linear increment to the retail prices, p_C^* and p_N^*, while keeping the difference between consumer utility, U_C and U_N, unchanged. In the blending strategy, however, the farmer purchases less the non-core product as c increases, which raises the perceived value, θ_B, as the proportion of the core product, z^*, increases. As θ_B rises, it justifies a higher retail price. Therefore, the farmer increases the price convexly to take the advantage of the monopoly of the blended product, the increased cost finally becomes a reason for a high margin. Consequently, p_B^* increases convexly with c, whereas p_C^* and p_N^* increase linearly, establishing $\tilde{c}$ as the threshold (Fig. 1b). Finally, as the yield y increases, p_C^* and p_N^* decrease as inventory concerns, while p_B^* rises with a higher θ_B. Therefore, the threshold $\tilde{c}(y)$ decreases in y.



(a) Demand Comparison (b) Price Comparison

Fig. 1. Price and demand comparisons (Note: $y = 0.15, \theta = 0.7$).

3.3.2. Retailing strategies comparison

In this Subsection, we examine when farmers engage in adulteration, what drives it, and under what conditions they maintain integrity without blockchain, addressed in the following proposition.

Proposition 4. *Without a blockchain traceability system, the farmer's profit under the blending strategy is always greater than the profit earned under the differentiating strategy, i.e.,* $\pi_B^* > \pi_D^*$.

Proposition 4 explains why the farmer acts opportunistically, favoring the blending strategy when traceability systems are absent. The fundamental driver of this behavior is the interplay between pricing and inventory structures. Mathematically, Lemma 1 indicates that a subset of consumers, despite having a positive utility to pay for the core product, ultimately opt for the non-core offering owing to low valuation induced by ambiguity. Compounding the cannibalization effect also exists in the core product's utility function, where a proportion of consumers choose to purchase the core product even with a positive utility of the non-core product. Consequently, the farmer faces a pricing conundrum under the differentiating strategy: setting prices too close intensifies internal competition, losing the quantity-driven profit from the non-core product; pricing them too far apart, however, focuses too much on the low-margin non-core product while diluting the margin-driven profit from the scarcity of the core product.[1] As a result, the farmer not only loses consumers with an extremely low willingness to pay, a loss that also occurs under the blending strategy, but also loses additional consumers due to product cannibalization. This creates an opportunity for the blending strategy: the farmer can set a retail price near that of the core product while selling quantities akin to those of the non-core product by exploiting the quality ambiguity, thereby extracting additional profit. Fig. 1 illustrates this numerically. To validate our results, we further conduct a robustness test with left- and right-skewed beta distributions in Appendix A.

4. The retailing strategy with blockchain

In the absence of a blockchain-based traceability system, it has been observed that consumers are forced to pay premium price for lower-quality agricultural product (Proposition 3), and the farmer are inclined to inclined to engage in dishonest practices (Proposition 4). To promote integrity and ensure fairness between consumer payments and their perceived value, centralized decision-making agents such as government can leverage blockchain technology to eliminate these dishonest practices. For example, in the green tea sector, blockchain can record every step of the product's lifecycle, from pest control and cultivation through harvest, processing, quality control to final sale, thereby eliminating opportunities for the unethical blending. In other words, with the implementation of a blockchain traceability system, the dishonest blending is eradicated, and farmer are guided to adopt the differentiating retail strategy.

Compared with the traditional differentiation strategy, adopting a blockchain-based traceability system (denoted by subscript β) leverages immutability to significantly reduce consumers' origin ambiguity, thereby homogenizing their evaluation and identification of product quality to the best level. Mathematically, since all consumers can access and trust the true quality information provided by the blockchain traceability system, the previously heterogeneous ambiguity parameter, υ, converges to a homogeneous value of $\upsilon = 1$.

The farmer now offers two types of products: the core product and the non-core product with the blockchain traceability system implemented. Since the core product is blockchain-verified, it eliminates consumer uncertainty and achieves a higher perceived quality. To cover the development costs of the blockchain system, the service provider charges a variable fee based on product transitions, with a unit transition cost, denoted by b, applied to each unit of the core product sold. To avoid trivial cases where a high

[1] We remark that the "close and far" refers to the percentile of the non-core product retail price relative to the core product retail price, though the numerical gap remains as a constant.

transaction fee results in extremely low profit, we restrict the maximum transaction fee that a service provider can charge, setting $b \in (0, 1 + c - \theta)$.

We also introduce the reputation cost r of selling the non-core product, whose quality is not as controllable as the core product. When the blockchain traceability system is implemented, the farmer who owns core plantations is discouraged from selling the non-core product alongside the core product, as this may lead to reputation loss or brand dilution (CustomerThink, 2024; ARD, 2024) for several reasons. With the blockchain traceability system, the food safety accident happens to the uncontrollable non-core product will be recorded and published, which significantly hurts the firm's reputation. For example, in March 2022, Hangzhou enforced the West Lake Longjing Tea Protection Regulation, which mandates non-transferable special identification codes, including producer information, production year, and unique serial numbers with anti-counterfeiting features, on every tea package to safeguard the authentic Longjing brand and protect local farmers' livelihoods. The firm can also prevent this accident by implementing necessary inspection to non-core product, during which the extra cost to preserve the firm's reputation is induced. We capture this deterrent effect by introducing a per-unit reputation cost r on all non-core sales. Furthermore, we can also extend the form of reputation cost to more general convex function, since the selling more non-core products increases the firm's probability exposed to the food safety accidents.

Consumers then choose among the core product, non-core product, or no purchase based on retail prices, aiming to maximize their utility. With the origin ambiguity eliminated, their utility functions become $U_{C\beta} = 1 \cdot 1 - p_{C\beta}$ and $U_{N\beta} = \theta \cdot 1 - p_{N\beta}$. The following lemma characterizes the demand for the core product and the non-core product under the utility-based model.

Lemma 2. *With the blockchain traceability system, the demand of the core product and non-core product under the differentiating retail strategy is given by:*

$$D_{C\beta}(p_{C\beta}, p_{N\beta}) = \Pr\left[U_{C\beta} > \max\{U_{N\beta}, 0\}\right] = \begin{cases} y, & \text{if } p_{C\beta} \le 1, \\ 0, & \text{if } p_{C\beta} > 1. \end{cases} \tag{10}$$

$$D_{N\beta}(p_{C\beta}, p_{N\beta}) = \Pr\left[U_{N\beta} > \max\{U_{C\beta}, 0\}\right] = \begin{cases} 1 - y, & \text{if } p_{N\beta} \le \theta, \\ 0, & \text{if } p_{N\beta} > \theta. \end{cases} \tag{11}$$

Comparing to the differentiating strategy without the blockchain traceability system, the main change reflects on the consumer side referring to the evaluation transfer from the heterogeneity to homogeneity. This basically means the consumers are identical upon the decision making process. Given the availability of the products, all consumers take the same buy-or-not-to-buy decisions. However, the core product products are offered in a sacred natural which means the number of consumers who are eligible to purchase is up to y. For the rest of consumers who do not get the chance to place the order, they will choose the non-core product if the utility is positive. Then, the farmer's maximization problem is formulated as the following:

$$\max_{p_{C\beta}, p_{N\beta} \ge c} \pi_{D\beta} = (p_{C\beta} - b) D_{C\beta}(p_{C\beta}, p_{N\beta}) + (p_{N\beta} - c - r) D_{N\beta}(p_{C\beta}, p_{N\beta}). \tag{12}$$

The profit function represents the farmer's total profit from selling both the core and non-core products. The term $(p_{C\beta} - b)\, D_{C\beta}(p_{C\beta}, p_{N\beta})$ captures revenue from the blockchain-verified core product, net of the per-unit traceability fee b. In practice, a government or market regulator may either provision the blockchain system centrally or contract it to a technology provider, where both way finally recoup development and maintenance costs via the service fee. To reflect these real-world arrangements, we incorporate the unit blockchain service cost b directly into the profit model. Additionally, the term $(p_{N\beta} - c - r) D_{N\beta}(p_{C\beta}, p_{N\beta})$ accounts for the profit from selling the non-core product, after subtracting the unit cost, c, and the reputation cost, r, with r capturing the strength of market supervision. The objective is to maximize this total profit by choosing the optimal retail prices $p_{C\beta}$ and $p_{N\beta}$. The following proposition summarizes the optimal pricing decisions and resulting profit under differentiated retailing with a blockchain traceability system.

Proposition 5. *Under the differentiating retailing with the blockchain traceability system, the farmer's optimal pricing decisions and profit are given by:*

$$\left\{ p^*_{C\beta}, p^*_{N\beta}, \pi^*_{D\beta} \right\} = \{1, \theta, (1 - b)y + (\theta - c - r)(1 - y)\}.$$

Proposition 5 is driven by the transparency and trustworthiness afforded by the blockchain traceability system. Under this regime, the core product can be priced at consumers' maximum willingness to pay, $p^*_{C\beta} = 1$, because its quality is fully verifiable. Although every consumer initially prefers the core product, limited supply restricts sales to only y units; the remaining consumers either purchase the non-core product at $p^*_{N\beta} = \theta$ if their utility remains positive or exit the market. Setting the non-core price to θ also extracts the highest willingness to pay from this residual demand. The optimal profit $\pi^*_{D\beta}$ then aggregates revenue from y core-unit sales and $(1 - y)$ non-core-unit sales, net of the blockchain service charge b, unit cost c, and reputation cost r. This pricing strategy ensures the farmer captures the full value of blockchain-enabled quality assurance.

4.1. Consumers' heterogeneous trust with blockchain adoption

Although our model captures blockchain adoption by homogenizing consumer willingness to pay to 1, empirical evidence suggests that residual trust issues may persist (Shen et al., 2021).

In this subsection, we model a realistic scenario where the consumer's willingness to pay are still subject to an ambiguity even after the blockchain adoption, and the v follows a uniform distribution $v \sim U[\underline{v}, 1]$, where $0 < \underline{v} < 1$ represents the minimal level of residual trust (lower $\underline{v}$ indicates greater trust issues), with density $1/(1-\underline{v})$. Therefore, the utility functions become $U_{C\beta'} = (1-v)\alpha + v - p_{C\beta'}$ and $U_{N\beta'} = \theta v - p_{N\beta'}$, where α ($\alpha \in (0, 1-\theta)$) captures the trust incremental from the blockchain adoption, and $\theta < 1$ is the non-core quality. Therefore, we modify the model as follows. (1) With blockchain adoption, the lower bound of consumers' willingness to pay increases from 0 to $\underline{v}$, reflecting enhanced trust generated by the technology. (2) Consumers remain heterogeneous in their willingness to pay, and utility is given by $U_{C\beta'} = (1-v)\alpha + v - p_{C\beta'}$, which indicates that consumers with initially higher willingness to pay benefit more from blockchain adoption compared with those with lower willingness to pay. This modification addresses the limitation of the previous setting where all consumers' willingness to pay was homogenized to 1.

Following this setup, the indifferent consumer between two products is located at $v_{CN} = (p_{C\beta} - p_{N\beta} - \alpha)/(1-\alpha-\theta)$, while the indifferent consumer between the non-core product and no purchase is at $v_{N0} = p_{N\beta}/\theta$. The resulting demands are $D_{C\beta'} = \min\left(y, \frac{1-v_{CN}}{1-\underline{v}}\right)$ and $D_{N\beta'} = \frac{v_{CN} - \max(\underline{v}, v_{N0})}{1-\underline{v}}$, where core supply is limited to y. The farmer's profit maximization problem is

$$\begin{aligned} \max_{p_{C\beta'}, p_{N\beta'}} \quad & \pi_{D\beta'} = (p_{C\beta'} - b)D_{C\beta'} + (p_{N\beta'} - c - r)D_{N\beta'}, \\ \text{s.t.} \quad & p_{N\beta'} \geq c + r, \\ & D_{C\beta'} \leq y. \end{aligned}$$

When $\theta\underline{v} \geq c + r$, the optimal solution satisfies $D^*_{C\beta'} = y$ and $D^*_{N\beta} = 1 - y$, with

$$\{p^*_{C\beta'}, p^*_{N\beta'}, \pi^*_{D\beta'}\} = \left\{ \begin{array}{l} \theta\underline{v} + \alpha + (1-\alpha-\theta)\big[1 - y(1-\underline{v})\big],\ \theta\underline{v}, \\ \big[\theta\underline{v} + \alpha + (1-\alpha-\theta)(1-y(1-\underline{v})) - b\big]y + \big(\theta\underline{v} - c - r\big)(1-y) \end{array} \right\}.$$

Furthermore, the sensitivity analysis yields:

$$\frac{\partial p^*_{C\beta'}}{\partial \underline{v}} = \theta + (1-\alpha-\theta)y > 0, \qquad \frac{\partial p^*_{N\beta'}}{\partial \underline{v}} = \theta > 0, \qquad \frac{\partial p^*_{N\beta'}}{\partial \underline{v}} = y[\theta + (1-\alpha-\theta)y] + (1-y)\theta > 0,$$

$$\frac{\partial p^*_{C\beta'}}{\partial \alpha} = 1 - \big[1 - y(1-\underline{v})\big] > 0, \qquad \frac{\partial p^*_{N\beta'}}{\partial \alpha} = 0, \qquad \frac{\partial p^*_{N\beta'}}{\partial \alpha} = y\big[1 - \big(1 - y(1-\underline{v})\big)\big] > 0.$$

Thus, higher $\underline{v}$ (greater trust, less heterogeneity) increases both prices and profit. Similarly, a higher α raises the core price and profit, while leaving the non-core price unaffected, as it enhances the attractiveness of the core product under low-trust conditions.

4.2. Endogenizing the blockchain adoption fee

Although this study focuses on the farmer's product design and pricing decisions when facing different technology-enabled transparency levels, we also discuss how the platform decides the blockchain adoption fee to meet the goal. The platform obtains the blockchain adoption fee from each unit of certificated core product, and thus, the farmer's income can be calculated as $\pi^*_{D\beta} = b \cdot D_{C\beta}$. Eq. (10) shows that the demand of the core product with the blockchain traceability system is always y given the optimal price is $p^*_{C\beta} = 1$. Therefore, the platform's income becomes $\pi^*_{D\beta} = b \cdot y$, where y is the yield of the core products, which indicates that with the blockchain, the firm will always set a price that clears all harvest. Since y is independent of b, the platform will charge the maximal adoption fee satisfying the firm's individual rationality (IR) constraints–the firm can gain more profit by adopting the blockchain traceability system than the benchmarks, i.e., $b^* = \max\{b | \pi^*_{D\beta} \geq \max\{\pi^*_B, \pi^*_D\}\}$. The IR constraint can be written as follows,

$$(1-b)y + (\theta - c - r)(1-y) \geq \max\left\{ \frac{(c + y + \theta - \theta y)^2}{4\theta} - c(1-y), (1-y)y - \frac{(\theta - c)^2}{4\theta} \right\}. \tag{13}$$

We will continue this discussion after comparing the firm's profits under different scenarios.

5. Comparative analysis: Demand, prices, and retailing strategy

The aforementioned analysis and results establish the farmer's equilibrium decisions and the corresponding profits under the subgame setting. In this section, we will comprehensively examine market demand, the farmer's retail pricing strategies, and profit comparisons across different retailing formats, aiming to determining whether a blockchain traceability system can realign the farmer's economic incentives toward honest business practices.

5.1. Market demand

While profit maximization remains the farmer's primary objective, it is essential first to consider consumer fulfillment. Proposition 4 shows that, in the absence of a blockchain traceability system, an opportunistic farmer maximizes profit by serving fewer consumers at a higher price for lower-quality products, resulting in a clear gap between what consumers pay and the value they receive. To quantify this effect, we define optimal fulfillment rates under the blending strategy (F^*_B), the differentiating strategy with blockchain ($F^*_{D\beta}$), and the differentiating strategy without blockchain (F^*_D), each measuring the proportion of demand met. The following proposition ranks these fulfillment rates across the three retailing strategies.

Proposition 6. *Under the three retailing strategies,*

1. *The ranking of the consumer's demand is* $D^*_{N\beta} > D^*_N > D^*_B > D^*_{C\beta} = D^*_C$;

2. *The ranking of the consumer's fulfillment rate is* $F^*_{D\beta} > F^*_D > F^*_B$.

By implementing the blockchain traceability system, consumers' ambiguity regarding the perceived product quality is fully eliminated, allowing the farmer under the differentiating strategy with the blockchain traceability system to serve all consumers in the market through reasonable pricing. In the case of the differentiating strategy without blockchain, the farmer can still expand sales of the non-core product by setting a relatively lower p^*_N, which attracts consumers who have higher ambiguity (low v) in their product evaluation. As shown in Propositions 1 and 2, the quantity of non-core product sold under the differentiating strategy exceeds that of the blending strategy. With the blockchain traceability system, the farmer can further fulfill 100 % of consumer demand under the differentiating strategy with blockchain traceability system, while the differentiating strategy without blockchain fulfills most demand, except for consumers with extremely high ambiguity. Therefore, under the differentiating strategy (with or without the blockchain traceability system), the farmer will prioritize the sales of the core product, and clear all the yield, y. The blending strategy uses monopolistic pricing to maximize profit but limits consumer reach.

5.2. Retail price

Given the market popularity and limited availability, the farmer can always sell its entire yield of the core product. Thus, the main purpose of pricing decisions is to regulate the quantity purchased from the outsider, ensuring that the supply aligns with the price-determined market demand while optimizing profit. The blockchain traceability system eliminates consumers' heterogeneity about product quality, thus aligning their willingness to pay to the best level, and leading the consistence buy-or-not-buy decisions based on the product's availability. To facilitate the analysis on retail prices, we first define several critical thresholds of the consumers' perceived quality, θ.

Lemma 3. *Given the* $\tilde{c}(y)$ *exists, and regarding retail prices as functions of* c,

1. *There exists a unique threshold,* $\theta_{B,N\beta}$, *such that* $p^*_{N\beta}(0) < p^*_B(0)$ *iff*[2] $\theta \in (c, \theta_{B,N\beta})$;
2. *There exists a unique threshold,* $\theta_{C,N\beta}$, *such that* $p^*_B(0) < p^*_{N\beta}(0) < p^*_C(0)$ *iff* $\theta \in (\theta_{B,N\beta}, \theta_{C,N\beta})$;
3. *For* $\theta \in (\theta_{C,N\beta}, 1)$, *there exists a unique threshold pair,* $(\tilde{\theta}_L, \tilde{\theta}_H)$, *that respectively solves* $p^*_{N\beta} = p^*_B(\tilde{c}(y)) = p^*_C(\tilde{c}(y))$ *and* $p^*_{N\beta} = p^*_C(c_\theta)$.

Given that $\tilde{c}(y)$ exists, indicating that p_B is not excessively high even in high-yield scenarios, we begin by defining the thresholds for the consumer's perceived value θ, with $c = 0$. Since $p_{N\beta} = \theta$, p_B and p_C respectively increase linearly and convexly, with respect to the unit purchasing cost of the non-core product c, it follows that $p_{N\beta}$ is initially the lowest when θ is sufficiently small. As θ increases, $p_{N\beta}$ starts to rise and eventually surpasses p_B and p_C within certain ranges of c. To further elaborate, the next lemma provides a detailed characterization of the conditions.

Lemma 4. *Given the* $\tilde{c}(y)$ *exists,*

1. *When* $\theta \in (c, \theta_{B,N\beta})$, $p^*_{N\beta} < \min\{p^*_B, p^*_C\}$;
2. *When* $\theta \in (\theta_{B,N\beta}, \theta_{C,N\beta})$, *there exists a unique threshold,* $\tilde{c}^L_{\theta B}$, *such that* $p^*_{N\beta} > p^*_B$ *iff* $c \in (0, \tilde{c}^L_{\theta B})$;
3. *When* $\theta \in (\theta_{C,N\beta}, \tilde{\theta}_L)$, *there exists a unique threshold pair,* $\tilde{c}^M_{\theta C}$ *and* $\tilde{c}^L_{\theta B}$, *that respectively solves* $p^*_{N\beta} = p^*_C(\tilde{c}^M_{\theta C})$ *and* $p^*_{N\beta} = p^*_B(\tilde{c}^M_{\theta B})$, *and* $\tilde{c}^M_{\theta C} < \tilde{c}^M_{\theta B}$;
4. *When* $\theta \in (\tilde{\theta}_L, \tilde{\theta}_H)$, *there exists a unique threshold pair* $(\tilde{c}^H_{\theta B}, \tilde{c}^H_{\theta C})$, *that respectively solves* $p^*_{N\beta} = p^*_B(\tilde{c}^H_{\theta B})$ *and* $p^*_{N\beta} = p^*_C(\tilde{c}^H_{\theta C})$, *and* $\tilde{c}^H_{\theta B} < \tilde{c}^H_{\theta C}$;
5. *When* $\theta \in (\tilde{\theta}_H, 1)$, *there exists a unique threshold,* $\bar{c}_{\theta B}$, *such that* $p^*_{N\beta} > p^*_B$ *iff* $c \in (\bar{c}_{\theta B}, c_\theta)$.

Building on Lemma 3, 4 further identifies the cost threshold at which the three retail prices intersect as c increases. In this setting, $p_{N\beta}$ is given by consumers' perceived quality of the non-core product, while the other prices increase with c. The following proposition formally presents the complete dynamics of these pricing strategies.

Proposition 7. *For a given* θ *and* $\tilde{c}(y)$ *exists,*

1. $p^*_{C\beta} > \max\{p^*_{N\beta}, p^*_B, p^*_C, p^*_N\}$, *and* $p^*_N < \min\{p^*_{N\beta}, p^*_B, p^*_C\}$;
2. *The ranking of the retail prices is presented in Table 6.*

Proposition 7 provides the ranking of retail prices across the three retailing strategies. Firstly, with the blockchain traceability system, the core product can capture all consumers' willingness to pay by setting $p^*_{C\beta}$ close to 1, thereby dominating the other retail prices. Additionally, although the farmer proactively discloses the true quality of non-core product, consumers still evaluate it with ambiguity in the absence of the blockchain traceability system. This ambiguity leads to a discounting effect on the willingness to pay that lowers the potential price ceiling for p^*_N, resulting in p^*_N being dominated by the other retail prices.

The ranking of the three retail prices, p^*_B, p^*_C, and $p^*_{N\beta}$, involves dynamic interactions. Since $p^*_{N\beta} = \theta$, it is directly determined by θ and remains the lowest price when the perceived value of the non-core product is low, for example, when $c < \theta < \theta_{B,N\beta}$. As

[2] Refer to as "if and only if".

Table 6
The ranking of $p_B^*, p_C^*, p_{N\beta}^*$.

θ Ranges	Conditions	c Ranges	Ranking
$c < \theta < \theta_{B,N\beta}$	$\tilde{c}(y) < c_\theta$	$c \in (0, \tilde{c}(y))$	$p_C^* > p_B^* > p_{N\beta}^*$
		$c \in (\tilde{c}(y), c_\theta)$	$p_B^* > p_C^* > p_{N\beta}^*$
$\theta_{B,N\beta} < \theta < \theta_{C,N\beta}$	$\tilde{c}_{\theta B}^L < \tilde{c}(y) < c_\theta$	$c \in \left(0, \tilde{c}_{CB}^L\right)$	$p_C^* > p_{N\beta}^* > p_B^*$
		$c \in \left(\tilde{c}_{CB}^L, \tilde{c}(y)\right)$	$p_C^* > p_B^* > p_{N\beta}^*$
		$c \in \left(\tilde{c}(y), c_\theta\right)$	$p_B^* > p_C^* > p_{N\beta}^*$
$\theta_{C,N\beta} < \theta < \tilde{\theta}_L$	$\tilde{c}_{\theta B}^M < \tilde{c}(y) < c_\theta$	$c \in \left(0, \tilde{c}_{\theta C}^M\right)$	$p_{N\beta}^* > p_C^* > p_B^*$
		$c \in \left(\tilde{c}_{\theta M}^M, \tilde{c}_{\theta B}^M\right)$	$p_\theta^* > p_{N\beta}^* > p_B^*$
		$c \in \left(\tilde{c}_{\theta C}^M, \tilde{c}(y)\right)$	$p_C^* > p_B^* > p_{N\beta}^*$
		$c \in \left(\tilde{c}(y), c_\theta\right)$	$p_B^* > p_\theta^* > p_{N\beta}^*$
$\tilde{\theta}_L < \theta < \tilde{\theta}_H$	$\tilde{c}(y) < \tilde{c}_{\theta B}^H < \tilde{c}_{\theta C}^H < c_\theta$	$c \in (0, \tilde{c}(y))$	$p_{N\beta}^* > p_C^* > p_B^*$
		$c \in (\tilde{c}(y), \tilde{c}_{\theta B}^H)$	$p_{N\beta}^* > p_B^* > p_C^*$
		$c \in \left(\tilde{c}_{\theta B}^H, \tilde{c}_{\theta C}^H\right)$	$p_B^* > p_{N\beta}^* > p_C^*$
		$c \in \left(\tilde{c}_{BC}^H, c_\theta\right)$	$p_B^* > p_C^* > p_{N\beta}^*$
$\tilde{\theta}_H < \theta$	$\tilde{c}(y) < \bar{c}_{\theta B} < c_\theta$	$c \in (\theta, \tilde{c}(y))$	$p_{N\beta}^* > p_C^* > p_B^*$
		$c \in \left(\tilde{c}(y), \bar{c}_{\theta B}\right)$	$p_{N\beta}^* > p_B^* > p_C^*$
		$c \in \left(\bar{c}_{\theta B}, c_\theta\right)$	$p_B^* > p_{N\beta}^* > p_C^*$

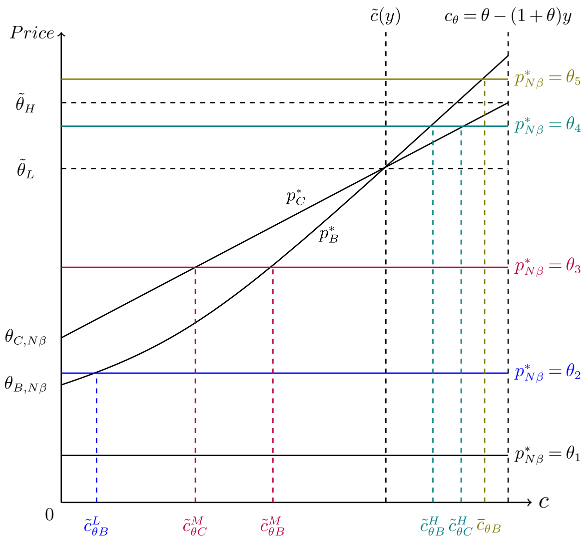


Fig. 2. Retail price comparisons.

demonstrated in Propositions 1 and 2, p_B^* and p_C^* respectively increase convexly and linearly with the increase of unit purchasing cost c. These price adjustments serve as reactive measures to mitigate rising costs and secure profits. When θ increases, $p_{N\beta}^*$ begins to rise and eventually surpasses p_B^* and p_C^* within certain lower ranges of c. Thus, with a higher perceived value of the non-core product, consumers are willing to pay more for it under the blockchain traceability system. When the consumer's perceived value of θ is low while the unit purchasing cost c is high, consumers benefit from the true quality assured by the blockchain traceability system and pay less. Conversely, when the consumer's perceived value of non-core product is high and the unit purchasing cost is low, the blockchain traceability system benefits the farmer more by enabling consumers to review and trust the true quality of the core product. When both θ and c are at intermediate levels and c is slightly low, consumers prioritize quality over price and are willing to pay $p_{N\beta}^*$ more than p_B^* and p_C^*, as a lower c indicates poorer quality (Mookerjee et al., 2021; Deval et al., 2013). However, when c is slightly high, the farmer seeks to compensate for the increased costs, leading to a pricing strategy where $\max\{p_B^*, p_C^*\} > p_{N\beta}^*$. Fig. 2 provides a visual example of the Proposition 7.

5.3. Farmer's profit

In addition to analyzing the price-determined demand and pricing strategies, this subsection presents results and insights from profit comparisons. According to Proposition 4, in the absence of a blockchain traceability system, the optimal profit from the differentiating strategy, π_D^*, is always lower than that of the blending strategy, π_B^*. Consequently, this subsection presents a comparative analysis of π_B^* and $\pi_{D\beta}^*$, exploring whether honest business practices force the farmer to accept lower profit. In other words, we examine whether the blockchain traceability system can effectively align the farmer's economic incentives with ethical business operations.

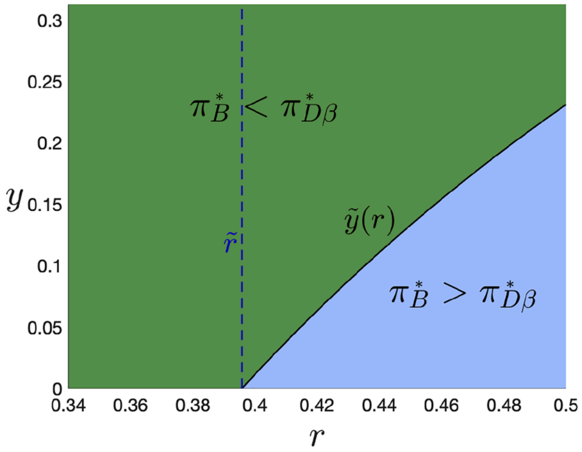


Fig. 3. Profit compare with farmer's reputation cost ($b = 0.2, c = 0.1, \theta = 0.6$).

Compared to the scenario without blockchain traceability, the system benefits consumers by enabling accurate quality assessments and eliminating ambiguity, thereby allowing the farmer to extend product availability to the entire market. The farmer experiences increased profit potential due to true value recognition in the market; however, they must incur costs associated with the value-adding services and the reputation cost on a transaction basis. Under the blending strategy, the farmer exploits the ambiguity in consumer evaluations and leverages monopolized pricing, facilitated by limited product accessibility, to sell mixed products at prices exceeding their true quality. The following proposition summarizes the relationship between π_B^* and $\pi_{D\beta}^*$.

Proposition 8. *There exists a threshold for the farmer's reputation cost, denoted by $\tilde{r} := \theta - \frac{(\theta+c)^2}{4\theta}$, and a threshold for the yield of the core product, denoted by $\tilde{y}(r)$,*[3] *such that:*

1. *When $r < \tilde{r}$, $\pi_{D\beta}^* > \pi_B^*$;*
2. *When $r > \tilde{r}$, $\pi_{D\beta}^* > \pi_B^*$ iff $y > \tilde{y}(r)$; otherwise, $\pi_{D\beta}^* \leq \pi_B^*$;*
3. *$\tilde{y}(r)$ is an increasing function of r.*

Proposition 8 demonstrates the pivotal role of the per-unit reputation cost r on non-core sales in shaping the farmer's strategy. When r lies below a critical threshold $\tilde{r}$, the differentiating strategy with blockchain traceability ($\pi_{D\beta}^*$) yields higher profit than the blending strategy (π_B^*), even after accounting for reputation penalties. Conversely, if $r > \tilde{r}$ and core yield y is low-i.e., scarcity is high-the premium earned on core sales cannot offset the heavy reputation cost, resulting in $\pi_B^* > \pi_{D\beta}^*$. This rationale rests on the fact that, if core-product sales fail to generate sufficient profit, the farmer is incentivized to revert to the dishonest blending strategy, exploiting the price-origin ambiguity to secure additional profit that exceeds $\pi_{D\beta}^*$. Furthermore, as r increases, the minimum core yield required for $\pi_{D\beta}^*$ to surpass π_B^* also rises, implying that harsher penalties demand greater yield to justify honest, blockchain-enabled sales. From what we derived, we see that the harsh penalty and the high scarcity cannot exist at the same time. While policymakers may be tempted to set high reputation costs to curb non-core sales during periods of scarcity, our analysis show that either with or without the blockchain traceability system, the selling quantity of the non-core product is indifferent of the both the yield quantity of the core product and the reputation cost. Thus, protecting the scarcity through implementing a high reputation cost is not quite effective. Additionally, our results also warn that the high reputation cost with excessive fines can backfire-prompting the farmer to revert to the blending strategy when core profits shrink. By contrast, a moderate reputation cost aligns the farmer's incentives with honest practices, facilitating smoother blockchain adoption and fostering transparency in the market. Fig. 3 provides an illustrative example of the Proposition 8.

By comparing the optimal profits with and without blockchain, we can also get the optimal blockchain adoption fee is $b^* = y + \frac{(\theta-c)^2}{4\theta y} + \frac{(\theta-c-r)(1-y)}{y}$. By charging this fee, the platform can squeeze all surplus of adopting the blockchain traceability system from the firm, that is, the firm will get the same profit with and without blockchain. However, in the long term, the firm is still willing to join the system to improve its reputation for producing core products.

5.4. Generalizing the reputation cost

We extend the linear reputation cost to a more general form, i.e., let $r(D_{N\beta})$ denote the reputation cost function with regard to the non-core demand. We suppose $r(\cdot)$ is a convexly increasing function, indicating that the marginal cost induced by food safety

[3] $\tilde{y}(r) = \dfrac{c(\theta-1)-\theta\left(2\sqrt{\dfrac{\theta\left(b^2+b(\theta-2r-1)+\theta^2-2\theta(r+1)+r(r+3)\right)-c(\theta-1)(b+\theta-r-1)+\theta-r}{\theta}}+2b+\theta-2r-1\right)}{(1-\theta)^2}$.

accidents or the reputation preservation increases in the demand and sales. Without loss of generality, we suppose $r'(1) \leq 1$ to restrict the overcharging of the reputation cost, that is, the maximal reputation cost for each unit of sales cannot exceed the consumer's maximal valuation. Then, the firm's profit function under the blockchain scenario can be written as follows:

$$\max_{p_{C\beta}, p_{N\beta} \geq c} \pi_{D\beta} = (p_{C\beta} - b)D_{C\beta}(p_{C\beta}, p_{N\beta}) + (p_{N\beta} - c)D_{N\beta}(p_{C\beta}, p_{N\beta}) - r(D_{N\beta}(p_{C\beta}, p_{N\beta})). \tag{14}$$

By checking the first-order condition of the profit function (14), the farmer's optimal pricing decisions and the profit tuple is $\{p^*_{C\beta}, p^*_{N\beta}, \pi^*_{D\beta}\} = \{1, \theta, (1-b)y + (\theta - c)(1-y) - r(1-y)\}$. This result shows the robustness of our model, since the firm makes the same decisions as the reputation cost is linear. We define $r^{-1}(\cdot)$ as the inverse function of reputation cost, then, the threshold for the yield of the core product defined in Proposition 8, $\tilde{y}$, solves the following equation,

$$y = 1 - r^{-1}\left[(1-b)y + \theta(1-y) - \frac{(c + y + \theta - \theta y)^2}{4\theta}\right].$$

The relationship between π^*_B and $\pi^*_{D\beta}$ preserves, i.e., $\pi^*_B < \pi^*_{D\beta}$ iff $y > \tilde{y}$; otherwise, $\pi^*_B \geq \pi^*_{D\beta}$.

6. Case study

This section presents an application example to demonstrate the actual operational scenarios between the blending strategy and differentiating strategy with a blockchain traceability system.

6.1. Background

There is a digital service company, referred to here as XH, which provides the blockchain traceability system for the Bojiakou Tea Trading Market in Rizhao, Shandong Province, China. The Bojiakou Tea Trading Market is the largest tea trading hub in northern China, integrating the trading of fresh leaves, finished (dried) tea, and other related services (The Paper, 2024). The tea industry is one of the key sector in Lanshan District, Rizhao, where the market is located. The region's tea plantations cover a total area of 10,800 hectares, including 10,467 hectares of mature tea gardens. There are 28,000 tea farming households, with an annual dried tea production of 55,000 tons. In 2022, the annual output value of the tea cultivation industry in Lanshan District reached 1.375 billion CNY (approximately 195 million USD), with an average yield exceeding 129,000 CNY per hectare (approximately 18,300 USD per hectare). The sales revenue of the tea industry reached 2.88 billion CNY (approximately 408 million USD)(China Post, 2023).

From the planting side, XH's blockchain traceability system includes a pesticide transaction platform where a registered farmer can only purchase a limited quantity of the pesticide based on the owned planting area through personal ID verification. This tactic aims to implement a strict quality control over chemical residuals to the core produce. From the transaction side, it includes an online transaction platform, a traceability scale, and rapid testing equipment capable of quickly detecting pesticide residues. Authorized local farmers are assigned a designated counter and a dealer card, granting them access to both the Bojiakou Tea Trading Market and the blockchain system (Bank of Rizhao, 2022). After each transaction, qualified finished tea that passes the rapid testing is issued a paper label embedded with traceability information for consumers. Payment can be made via a QR code displayed on the traceability scale, and the farmer receives the revenue after transaction fees are deducted. The system was adopted in early 2022, and it now has regurgitated 19,200 tea farming households and enterprises.

6.2. Farmer's profit

Based on the analysis of transaction data from XH's management team, the average retail price of Rizhao green tea from the core area is 657 CNY per kilogram (approximately USD 92). Although the use of the traceability scale is free, XH charges 13 % of the transaction to cover the cost of software development, traceability scale manufacturing, and chemical test materials. As we normalized the retail price of the core product, with the blockchain traceability system, to 1, then we correspondingly normalize the blockchain service charge as $b = 0.13$. During a field visit to the Bojiakou Tea Trading Market, it was recorded that the purchasing cost of fresh leaves from non-core areas is about 46 CNY (approximately USD 6.5) per kilogram. The conversion rate from fresh tea leaves to dried tea is typically 5:1, meaning 5 kg of fresh leaves are needed to produce 1 kg of finished tea. Therefore, the value of c is calculated and scaled to $46 \cdot 5/657 = 0.35$.

It is important to note that tea from non-core production areas does not necessarily imply lower quality; in fact, it can be a more affordable option for consumers. Core production areas are considered more authentic due to geographical and cultural recognition, which grants them higher cultural value and social prestige, often leading to higher prices. According to discussions with staff at the Rizhao Tea Research Institute, nutrient levels such as tea polyphenol content in tea from non-core areas are not significantly different from those in core areas. However, factors like taste and leaf shape can cause consumers to perceive the quality as lower, approximately around 70 % of that from core areas. We provide the estimate methodology from empirical evidence and retail prices, detailed in the Appendix A. Consequently, θ is set to 0.70.

Moreover, although Rizhao boasts over 20,000 hectares of tea plantations, not all gardens-even within Lanshan District-qualify as core production areas. Specifically, Lanshan District contains approximately 10,800 hectares of tea plantations (Xinhua News Agency, 2023), with roughly half designated as core production areas. Additionally, due to stricter pesticide use standards, the yield per unit area of tea plantations in core production areas is approximately 90 % of that in non-core areas. Meanwhile, data from XH's traceability

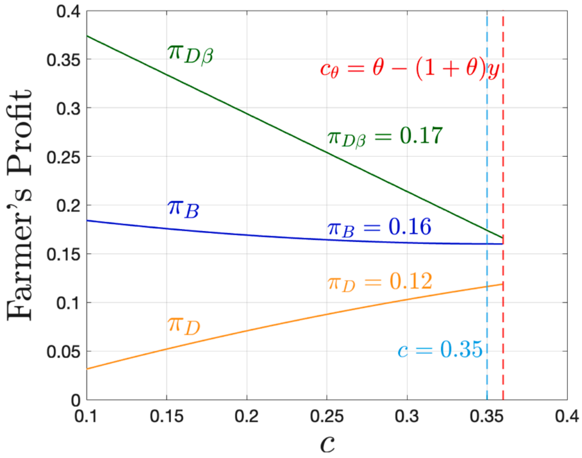


Fig. 4. Farmer's profit under three retailing strategies ($y = 0.22, \theta = 0.70, b = 0.13, r = 0.35$).

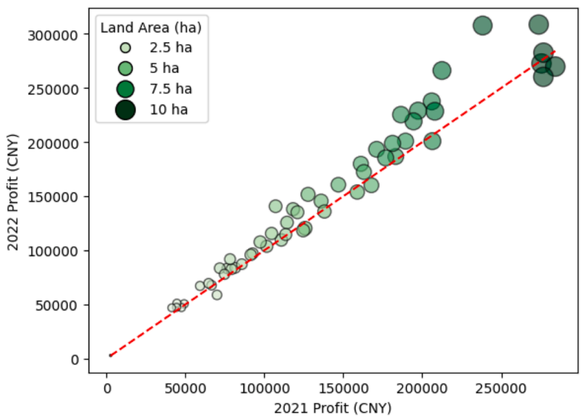


Fig. 5. Farmer's profit comparison between 2021 and 2022.

system's rapid testing equipment shows that 17.4 % of the local fresh leaves failed to meet core area certification due to issues like excessive or uneven pesticide residues. Therefore, y is calculated as 0.22. Finally, during conversations with local farmers, we learned that selling the non-core products bearing the local geographical indication label in the core area can trigger punitive measures-such as confiscation-by market regulators or government authorities. Therefore, we approximate the reputation cost as the cost of sourcing raw materials from non-core areas, setting $r = 0.35$. With these collected data, we are now ready to perform the analysis, and evaluate the farmer's profit, checking if it is really improved by adopting the blockchain traceability system. We present the result in the following figure.

Fig. 4 compares the farmer's current normalized profits under the blending strategy and the differentiating strategy with/without a blockchain traceability system. The results show that even as the non-core tea's purchasing cost c closes to its theoretical upper bound, the differentiating strategy with the blockchain traceability system still yields approximately 6.26 % higher profit, compared to the blending strategy. The numerical example illustrates a scenario where, without the blockchain traceability system, the farmer would be inclined to adopt the blending strategy, as $\pi_B > \pi_{D\beta}$, indicating that honesty is not incentivized, as consumers' willingness to pay with the ambiguity is discounted. However, by implementing the blockchain traceability system, revealing the true quality helps consumers to make informed decisions, thereby rewarding the farmer for selling with integrity and leading to higher profits.

In addition to the analysis based on our model, we further conduct a statistical analysis to empirically examine whether the blockchain traceability system is beneficial for farmers. We obtain the transaction-level data directly from the service provider, XH. Due to the space limitation, the detailed data description is exhibited in Appendix A. This data set encompasses 57 farmers in Shandong Province over a 14-day harvesting period in both Spring 2021 (pre-blockchain adoption, characterized by blending practices) and Spring 2022 (post-adoption, with blockchain-enabled origin traceability). The analysis includes comparative pre-/post-statistics on profit margins, adulteration rates, related metrics, and regression modeling. The next figure provides a profit comparison.(Fig. 5)

From the results, 78.95 % of farmers saw higher profits, with an average increase of 7.25 %. Profits in 2022 were significantly higher than in 2021, as confirmed by a paired t-test yielding $t = 4.69$ and $p < .001$; the 95 % confidence interval for the mean difference is

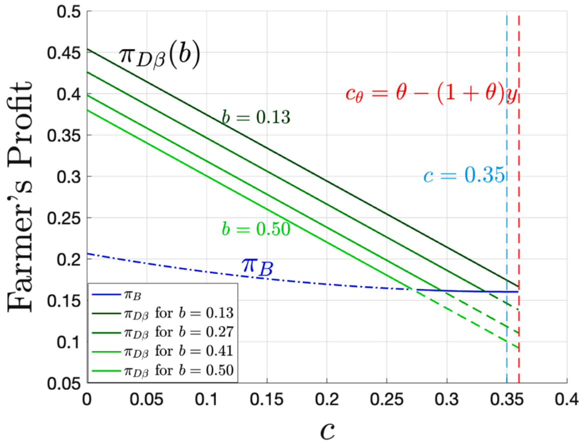


Fig. 6. Sensitivity analysis of the farmer's preference under different b ($y = 0.22, \theta = 0.70$, $r = 0.35$).

[5695.54, 13867.64] CNY, entirely above zero. We also estimate the adulteration rate at 8.36 %, which the system effectively eliminates with the blockchain adoption. We kindly advise the reader to Appendix A for more details.

6.3. Sensitivity analysis

Discussions with XH's management revealed that government subsidies were essential to launching its blockchain traceability system, which combines digital, mechanical, and chemical components. Without subsidies, XH estimated it would need to charge transaction fees up to 41 %-a level that would likely deter adoption and highlight the risks of monopoly pricing in such local markets. This raises an important question of how varying fee rates shape farmers' profit-maximizing behavior. To examine this, we conduct a sensitivity analysis by varying fees from the current 13 % up to 50 %, as shown in the figure below.

As shown in Fig. 6, an increase in the transaction fees charged by the service provider will reduce the profit under the differentiating strategy with the blockchain traceability system, thereby lowering the threshold for switching to the blending strategy. If XH were to actually charge a 41 % transaction fee in the absence of government subsidies, the farmer would be unwilling to adopt the blockchain traceability system and would remain with the blending strategy. In this scenario, total consumer demand would decrease, and consumers would end up paying more for a product without accurately reflecting its true quality.

The analysis presented in Fig. 6 reveals another important insight: when the service provider must charge a high transaction fee, a potential approach to mitigate the negative impact on farmers who adopts the blockchain traceability system is to reduce the cost of purchasing the non-core product. In the corresponding scenario, with $b = 0.41$ and $c = 0.35$, $\pi_{D\beta}$ is lower than π_B. However, such the situation could be improved by lowering c. Although in our research c is treated as an exogenous variable, the government can influence it by expanding the planting area of the non-core product beyond the core plantation region, with the aim of lowering c through the increased supply.

In fact, the local government has adopted another smart approach by subsidizing pesticides through a real-name registration system for both the core and non-core cultivation (Agricultural, 2024).[4] This policy not only enforces food safety standards for agricultural products but also helps reduce the farming costs, thereby lowering c on the market. From a practical standpoint, government and market regulators can incentivize honest farming practices by subsidizing either the blockchain technology itself or the farmer directly, instead of adding the cost to the non-core product, which finally can backfire the ethical business operations.

7. Conclusions

This study highlights the potential of the blockchain-enabled traceability system within the premium agricultural market, focusing on their impact on retailing strategies and integrity of the premium agricultural market. As consumer demand for origin-verified and authentically produced products continues to grow, blockchain technology provides a promising solution to persistent issues such as blending and adulteration. By embedding traceability and transparency into the agricultural supply chain, blockchain empowers the farmer to engage in honest quality differentiation rather than opportunistic blending strategies.

Our analysis reveals that, without blockchain, the farmer under the differentiating strategy consistently charges a premium price to capture extra margin from consumers with high willingness to pay. Moreover, when consumer ambiguity exists, the farmer is often driven to adopt blending strategies-mixing the non-core products with premium ones-which, while profitable, erodes consumer trust and undermines market integrity. The introduction of blockchain traceability transforms this dynamic by providing verifiable quality

[4] Farmers can only purchase a certain amount of pesticides based on the planting area they own, verified by their ID. Any excess purchase beyond the government limit is prohibited and could result in significant fines if discovered.

information. This transparency enables the farmer to leverage genuine quality differentiation, reinforce consumer confidence, and sustain premium pricing. Finally, when considering the reputation cost imposed by the market regulator, our results suggest that the reputation cost, stemmed form the supervision intensity, should be relaxed to encourage the farmer, especially those with low yields, to adopt blockchain traceability systems; otherwise, overly strict supervision may prove counterproductive. The real-world case study of a tea market demonstrates how blockchain adoption can practically deter dishonest practices while enhancing profitability by aligning economic incentives with the honest conduct. When consumers can trust the product's origin, the farmer is rewarded for maintaining high-quality standards, effectively balancing profitability with honest business operations. Additionally, our findings suggest that transaction cost associated with the blockchain service is the critical factor in adoption decisions. In scenarios where these costs are prohibitive, the farmer may revert to blending strategies. Thus, practical support mechanisms, such as government subsidies demonstrated by the case study, could play a vital role in promoting blockchain adoption across agricultural sectors.

This research complements the literature on agricultural supply chain transparency by providing both theoretical and practical implications for practitioners seeking to bolster integrity in premium agricultural markets. By demonstrating how blockchain can bridge the gap between profitability and honest business practices, our study underscores its potential as a strategic tool that benefits both the farmer and consumers.

Our study can be extended in the following dimensions. While our current model treats the (per-code) blockchain service fee as exogenous, extensions could explore dynamic blockchain fee structures-such as quantity discounts or two-part tariffs-and assess their impacts on adoption thresholds and overall welfare. Similarly, incorporating competition among traceability platforms (e.g., with two-sided network effects or multi-homing) and endogenizing the service fee b could reveal alternative equilibrium prices and market dynamics. Alternative decision-maker objectives are also worth examining: for instance, regulators might prioritize minimizing adulteration under budget constraints, whereas cooperatives could emphasize maximizing farmer surplus. Pursuing these directions would further enrich the model's policy implications.

CRediT authorship contribution statement

Zijian Zhao: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization; **Yunzhe Qiu:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing; **Pengcheng You:** Funding acquisition, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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E-Companion to "From Ambiguity to Transparency: Blockchain-Enabled Origin Traceability for Premium Agricultural Product"

The e-companion consists of three parts. In Appendix A, we provide the supplementary analysis adhere to our case study, empirical analysis, and parameter justifications. In Appendix B, we provide a detailed explanation of why the defined yield upper bound is reasonable in our setting. And Appendix C gives the proofs of the statements in the main paper.

Appendix A. Supplementary Materials of the Case Study

A.1. Data description and methodology

We have expanded the case study with a comprehensive empirical analysis using transaction-level data obtained from the service provider, XH. This data encompasses 57 farmers in Shandong Province over a 14-day harvesting period in both Spring 2021 (pre-blockchain adoption, characterized by blending practices) and Spring 2022 (post-adoption, with blockchain-enabled origin traceability). The analysis includes comparative pre-/post-statistics on profit margins, adulteration rates, related metrics, and a regression model. Below, we detail the data, methodology, and key findings, incorporated into Subsection 6.2.

For the post-blockchain adoption data, it is sourced directly from XH's platform, including farmers' transactional level data with a large tea manufacturer who procures fresh leaves from these farmers in 2022. And the pre-blockchain adoption data are drawn

Table A.1
Daily transactions for farmer 1 (land_area_ha: 9.87, salvage_ratio_2022: 0.9145).

Year	Day	Quantity (kg)	Qualified (kg)	Salvage (kg)	Price (CNY/kg)	Revenue (CNY)	Cost (CNY)	Fee (CNY)	Profit (CNY)	Tea Type
2021	1	220.53	0.00	0.00	224	49399.71	26854.23	0.00	22545.49	blended
2021	2	204.37	0.00	0.00	220	44960.70	24882.01	0.00	20078.69	blended
2021	3	256.50	0.00	0.00	218	55917.70	31352.55	0.00	24565.15	blended
2021	4	207.88	0.00	0.00	218	45317.18	25392.15	0.00	19925.03	blended
2021	5	267.91	0.00	0.00	218	58403.57	32885.75	0.00	25517.82	blended
2021	6	143.86	0.00	0.00	212	30498.00	17922.69	0.00	12575.30	blended
2021	7	275.89	0.00	0.00	216	59591.91	33671.29	0.00	25920.63	blended
2021	8	168.09	0.00	0.00	208	34963.42	20791.44	0.00	14171.98	blended
2021	9	202.42	0.00	0.00	206	41698.16	24755.22	0.00	16942.94	blended
2021	10	165.80	0.00	0.00	210	34817.19	20482.68	0.00	14334.50	blended
2021	11	240.12	0.00	0.00	208	49944.33	29276.99	0.00	20667.34	blended
2021	12	227.72	0.00	0.00	206	46910.64	27734.45	0.00	19176.19	blended
2021	13	242.83	0.00	0.00	206	50023.18	29673.56	0.00	20349.63	blended
2021	14	203.97	0.00	0.00	206	42017.78	24994.53	0.00	17023.26	blended
2022	1	227.64	188.03	39.61	266	59650.25	27316.33	6501.99	25831.93	qualified/salvage
2022	2	223.04	184.23	38.81	256	56248.87	26764.90	6131.23	23352.75	qualified/salvage
2022	3	214.47	177.15	37.32	270	57045.56	25736.52	6218.07	25090.97	qualified/salvage
2022	4	199.28	164.60	34.67	266	52218.62	23913.08	5691.93	22613.62	qualified/salvage
2022	5	196.95	162.68	34.27	260	50445.88	23634.37	5498.69	21312.81	qualified/salvage
2022	6	217.92	180.00	37.92	262	56245.44	26150.36	6130.86	23964.22	qualified/salvage
2022	7	202.95	167.64	35.31	260	51982.49	24354.29	5666.19	21962.01	qualified/salvage
2022	8	220.41	182.06	38.35	252	54716.57	26449.05	5964.21	22303.32	qualified/salvage
2022	9	181.91	150.25	31.65	254	45516.69	21828.74	4961.40	18726.55	qualified/salvage
2022	10	99.49	82.18	17.31	258	25287.71	11939.37	2756.41	10591.93	qualified/salvage
2022	11	234.23	193.47	40.76	258	59531.53	28107.29	6489.05	24935.19	qualified/salvage
2022	12	278.76	230.26	48.50	250	68653.29	33451.30	7483.34	27718.65	qualified/salvage
2022	13	211.05	174.33	36.72	252	52394.21	25326.46	5711.07	21356.69	qualified/salvage
2022	14	190.05	156.98	33.07	250	46805.54	22805.99	5101.89	18897.66	qualified/salvage

from the bookkeeping records of a major tea manufacturer that engages with farmers on an annual basis. Due to pandemic-related protocols, only the 2021 data meet the quality requirements for our analysis.

By comparing the two years of data, we identified 57 farmers who maintained complete transaction records with the tea manufacturer across both years. We specifically focus on a two-week fresh-leaf trading period that typically occurs in mid-April. The dataset records, on a daily basis, each farmer's fresh-leaf quantity, selling price, and (for 2022 only) salvage quantity. The key variables include:

- Farmer-specific attributes: land area, salvage ratio (for 2022, recording the percentage of the fresh tea leaves that passed the quality control).
- Daily transaction data: production quantity (kg), qualified/unqualified/salvage quantities (kg), price per kg (CNY, irregular daily values), daily revenue, blockchain fee (13 %), and final profit.

The dataset comprises 1596 observations (57 farmers × 14 days × 2 years). All analyses were conducted using Python. We modeled the pre- and post-adoption scenarios to quantify blockchain's impact on profitability and adulteration:

- 2021 (Pre-Adoption, Blending): Farmers blended their core tea (cost: 200 CNY/kg, with less pesticide input and lower yield), and procured non-core tea (cost: 230 CNY/kg). Total quantity = own + additional; revenue = quantity × price; cost = (own × 200) + (additional × 230); profit = revenue - cost (no fee).
- 2022 (Post-Adoption): Only own production, with 17.4 % unqualified tea salvaged at a discounted price. Qualified revenue = qualified quantity × price; total revenue = qualified + salvage revenue; cost = own quantity × 200; fee = qualified revenue × 0.13; profit = revenue - cost - fee.
- The adulteration rate, as the business privacy of the farmer, is hard to obtain directly. However, after the traceability system was adopted, farmers' owned core planting area is recorded, thereby we estimate the annual production volume for each farmer. Based on the total revenue and profit the farmer earned in 2021, we can backwardly calculate the difference between the revenue the farmer "should" earn and "actually" earned. And we can infer the gap that directly corresponds to the non-core quantity procured for blending. We believe this methodology provides a well-founded estimation of the adulteration rate.

First, we provide a sample farmer data set as Table A.1. We see the retail price of the fresh leaves increases about 17 % compared to 2021, with pre-blockchain traceability adoption. And the on-site rapid text indicates 8.55 % fresh leaves that do not pass through the chemical check. Although the stricter protocol constrained the qualified production quantity, this farmer still achieved a 12.75 % increase in profit compared to 2021, notably higher than the 7.25 % average profit growth observed across the entire group.

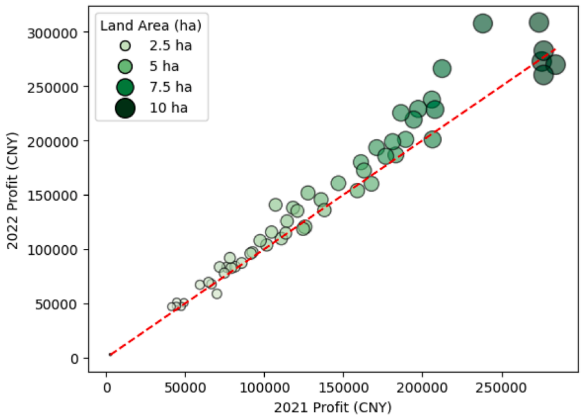

Fig. A.1. Farmer's profit comparison between 2021 and 2022.

A.2. *Regression model for Farmers' profit*

Additionally, we present a comprehensive comparison of farmers' profits before and after blockchain adoption between 2021 and 2022 in Fig. A.1.

- From the statistical results, we observe 78.95 % farmers experienced an increase in profit relative to the previous year, with the average profit growth reaching 7.25 %. And there is strong statistical evidence that farmers' profits in 2022 (with blockchain adoption) are significantly higher than in 2021 (without blockchain), with a paired t-test yielding $t = 4.69$ and $p < .001$. The 95 % confidence interval for the mean profit difference is $[5695.54, 13867.64]$ CNY, which lies entirely above zero, thereby providing the statistical evidence that blockchain adoption is associated with an increase in farmers' profits, validating our conclusions.

A.3. *Adulteration estimation*

To best estimate the farmer's adulteration ratio in 2021, we first use the total yield quantity in each day (as a reference point) × the corresponding fresh leaves' retail price - cost = "should earn" profit. Then we use the actual profit in 2021 - "should earn" profit = estimated extra profit from blending. Finally, we use the estimated extra profit from blending / the average retail price of the fresh leaves from the adjacent market = estimated blending quantity. As for the salvage ratio data, it is extracted from the XH's dataset, which is recorded during the transactional process. All the relevant data is appended in the Table below.

As shown in Table A.2, the average adulteration ratio across the farmer group is 8.36 %. This aligns with the intuition of local industry practitioners: while additional blending can increase the overall supply quantity, it simultaneously raises the risk of detection by the manufacturer through the dried tea's shape and aroma. Interestingly, all farmers appear to tacitly maintain their adulteration ratio near this average, as reflected in a relatively low coefficient of variation of 6.27 %.

A.4. *Estimation for θ and c*

Furthermore, we conducted a field visit to the manufacturer's branded retail store in the city and examined the product portfolio under their differentiation strategy. According to the store staff, tea sourced from non-core regions does not exhibit substantial differences in nutrition or external quality. Instead, attributes such as taste, aroma, and leaf shape, which are closely tied to the specific production origin, play a more decisive role in shaping consumer perception and are reflected in substantial variations in retail prices. Based on this observation, we estimate consumers' perceived value as $\hat{\theta} = \frac{\text{average non-core price}}{\text{average core price}} = 0.6887$, which is close to the case study estimation of $\theta = 0.7$.

For the purchasing cost of non-core materials, according to XH's database, the retail price of dried tea from the core area is 657 CNY per kg across the entire market, while the average purchasing price from the non-core area is recorded as 46 CNY per kg.[5] Given that producing 1 kg of dried tea typically requires 5 kg of fresh leaves, we estimate the non-core material cost as $c = \frac{46\times5}{657} \approx 0.35$.

To summarize, we enriched Section 6 with transaction-level evidence and empirical calibration. Using a balanced panel of 57 farmers over a two-week harvest window in 2021 (pre-adoption) and 2022 (post-adoption; 1596 observations), we document that 78.95 % of farmers increased profits, with an average gain of 7.25 %. A paired t-test confirms a significant improvement ($t = 4.69$, $p < .001$), and the 95 % confidence interval for the mean profit difference $[5695.54, 13867.64]$ CNY lies strictly above zero. We quantify

[5] The average core-originated tea with retail price of 657 CNY per kg reflects sales across the entire season-spring, summer, and autumn-where prices peak in spring and taper off in the subsequent seasons.

Table A.2
Adulteration and salvage ratios for 57 farmers.

Farmer ID	Land Area (ha)	Total Qty 2021	Blending Qty	Adulteration Ratio	Salvage Ratio 2022
1	9.87	3027.89	244.11	0.0806	0.9145
2	3.16	1026.27	75.77	0.0738	0.8628
3	3.42	1020.93	91.27	0.0894	0.9108
4	1.78	547.37	42.88	0.0783	0.7796
5	7.60	2287.93	189.10	0.0827	0.9402
6	0.10	28.60	2.52	0.0881	0.8810
7	10.17	3039.22	243.18	0.0800	0.8162
8	2.72	851.51	69.98	0.0822	0.8791
9	5.96	1786.56	149.45	0.0837	0.8340
10	4.25	1195.77	103.13	0.0862	0.9305
11	9.39	2657.13	228.01	0.0858	0.9616
12	0.10	30.48	2.59	0.0850	0.9677
13	4.03	1222.96	100.58	0.0822	0.7283
14	3.85	1130.13	96.00	0.0849	0.7245
15	8.40	2318.10	220.67	0.0952	0.7996
16	1.70	524.43	39.94	0.0762	0.8528
17	4.48	1314.19	114.02	0.0868	0.9101
18	2.37	740.59	64.56	0.0872	0.8653
19	5.13	1495.78	130.49	0.0872	0.7129
20	6.75	2105.31	165.08	0.0784	0.8155
21	1.70	494.22	39.52	0.0800	0.9062
22	8.43	2361.70	193.03	0.0817	0.8584
23	7.70	2202.72	199.50	0.0906	0.9010
24	6.51	2021.24	159.79	0.0791	0.8222
25	7.70	2168.05	193.23	0.0891	0.8239
26	2.95	800.36	76.60	0.0957	0.8549
27	4.63	1530.45	125.41	0.0819	0.8728
28	2.19	656.44	54.01	0.0823	0.8559
29	4.20	1269.15	108.41	0.0854	0.8495
30	6.59	1891.74	172.37	0.0911	0.7863
31	2.93	904.21	71.89	0.0795	0.8702
32	3.81	1255.22	103.02	0.0821	0.8497
33	2.94	951.34	67.33	0.0708	0.9304
34	2.46	717.97	64.23	0.0895	0.9359
35	2.99	881.37	73.34	0.0832	0.8548
36	4.96	1402.14	123.42	0.0880	0.8100
37	1.65	491.00	40.48	0.0824	0.7889
38	5.70	1854.66	141.24	0.0762	0.8739
39	9.98	3069.03	240.85	0.0785	0.8462
40	7.23	2066.48	182.67	0.0884	0.8125
41	4.42	1384.65	120.84	0.0873	0.8435
42	2.34	776.41	61.90	0.0797	0.7904
43	2.76	825.68	64.99	0.0787	0.8958
44	10.03	3138.89	249.02	0.0793	0.8042
45	5.15	1424.98	130.29	0.0914	0.9380
46	3.09	864.68	72.48	0.0838	0.8723
47	5.57	1641.32	146.82	0.0895	0.8875
48	9.97	3072.42	249.46	0.0812	0.7524
49	5.36	1744.17	126.28	0.0724	0.8536
50	6.85	1999.91	173.99	0.0870	0.8992
51	5.90	1806.81	152.10	0.0842	0.7637
52	3.94	1158.42	93.80	0.0810	0.8187
53	1.57	455.06	35.03	0.0770	0.8426
54	3.95	1084.32	94.30	0.0870	0.7302
55	4.37	1352.28	117.50	0.0869	0.8652
56	6.76	1976.40	169.69	0.0859	0.9077
57	7.52	2295.17	186.30	0.0812	0.7712
Average	–	–	–	0.0836	0.8496

adulteration in 2021 via a profits-based back-out method and report an average adulteration ratio of 8.36 % with low dispersion (CV = 6.27 %) in Table A.2; 2022 salvage ratios are taken directly from platform logs. To validate model parameters, we empirically anchor θ using disjoint core vs. non-core retail prices (Table A.3), yielding $\hat{\theta} = 0.6887 \approx 0.70$, and compute the non-core cost share c yields ($c = (46 \times 5)/657 \approx 0.35$). These additions provide the requested statistical analysis, pre-/post-comparison, and parameter validation, thereby strengthening our case study with practical insights.

Table A.3
Dried tea retail price under the differentiating strategy.

Product	Category	Price (CNY/500g)
Core		
Product A	Core	1399.00
Product C	Core	1099.00
Product E	Core	899.00
Product G	Core	599.00
Non-core		
Product B	Non-core	988.00
Product D	Non-core	888.00
Product F	Non-core	588.00
Product H	Non-core	288.00
	Average Core Price	**999.00**
	Average Non-core Price	**690.50**
	Estimated θ	**0.6887**

A.5. Cross-category analysis

We expand the discussion section to further analyze the applicability of our conclusions in high-end segments with other premium agricultural products. We have incorporated specific data on farmer profit increases from certifications, drawing from peer-reviewed studies and reports, to strengthen the evidence base.

One clear parallel exists with the specialty coffee market, where origin traceability and quality tactics mirror those in high-end tea. For instance, certifications such as Fair Trade, Rainforest Alliance, and Organic are prevalent in both sectors. A study on Fair Trade certification in Costa Rica found that it leads to a 2.2 % increase in average incomes for farm owners, with net benefits ranging from \$45 to \$124 per year per farmer (equivalent to 1.92 % to 5.51 % of annual income), even after accounting for certification costs of about \$2 per farmer annually (Dragusanu et al., 2022). Real cases, such as Colombian coffee's use of the traceability system like Café de Colombia, demonstrate how origin-based branding, akin to our tea study, creates competitive advantages in premium markets.

In the fine wine sector, our findings on terroir-driven branding resonate strongly, as wine has long leveraged its origin to command premium prices. For example, European wines under appellations like Bordeaux or Chianti emphasize origin and quality controls, paralleling Darjeeling tea's GI, which protects against imitation and supports higher margins. A cross-commodity analysis shows that wine's bottom-up sustainability movements-originating from growers' environmental concerns-contrast with tea and coffee's more top-down approaches driven by global standards, yet both lead to comparable outcomes in consumer loyalty and support the premium retail in the global market. Studies indicate that sustainability certifications like USDA Organic or SIP (Sustainability in Practice) enhance market positioning and can increase winery revenues through premium branding, with one review noting improved product quality and reputation as key drivers of economic benefits (Mariani and Vastola, 2015).

Extending beyond beverages, our conclusions also apply to other high-end agricultural products like premium olive oil and single-origin chocolate, where origin labeling and traceability drive consumer preferences. In the olive oil market, extra-virgin varieties from regions like Tuscany or Andalusia use branding strategies focused on authenticity and health benefits. The manufacturer's traceability program enables access to European funding, such as the 28 million euros allocated in Italy's 2015–2017 national olive plan for tracability practices, allowing producers to invest at reduced costs and position products in premium segments with average prices of 3.76 €/kg-higher than competitors like Spain (2.5 €/kg)-due to consumer willingness to pay for certified quality (Lombardo et al., 2021). For chocolate, traceability for sustainability (e.g., Rainforest Alliance) ensures ethical sourcing, with VSS-compliant cocoa farmers obtaining up to 30 % higher prices than conventional growers, alongside positive effects on net cocoa income (Development, 2022; Waarts et al., 2025).

This analysis underscores that while contextual differences exist-such as coffee's north-south trade versus wine's north-north patterns-our core conclusions on leveraging the origin traceability for market differentiation hold across the aforementioned agricultural products, benefiting farmers' profit, and enhancing the generalizability without diluting the tea case study's depth.

Appendix B. Explanation of $y \in \left[0, \frac{\theta}{1+\theta}\right]$

Before going to the proofs, we justify why defining $y \in \left(0, \frac{\theta}{1+\theta}\right]$ has a rationale rooted in consumer utility, blending feasibility, and market absorption constraints. Here's why the ratio $\frac{\theta}{1+\theta}$ is used specifically.

The farmer blends core ($\mathbb{C}$) and non-core ($\mathbb{N}$) products, and the total market supply under the blending strategy is:

$$Q_B = \frac{y}{z}.$$

The blending ratio z represents the share of the core product in the final blend, and the non-core portion is filled with purchases from the external market. We require: $Q_B = y/z \leq 1$, where the market can fully absorb it, as the farmer does not have the motivation to blend the quantity that exceeds the market potential. Then, we have $y \leq z$. To be as generous as possible, we want to find the largest possible value of y such that supply remains within market limits for all feasible blending ratios z. The perceived quality of the blend is:

$$\theta_B = z \cdot 1 + (1 - z) \cdot \theta = \theta + z(1 - \theta)$$

Consumers with utility $U_B = \theta_B v - p_B$ will purchase the product if their type $v \geq \frac{p_B}{\theta_B}$. To maximize the market absorption, one reasonable point is to balance the weight of the low-quality (θ) and high-quality (1) components. A natural balancing point is when: Quality weight ratio: $\frac{z}{1-z} = \frac{1}{\theta} \Rightarrow z = \frac{1}{1+\theta}$. This is not arbitrary–it is the blending proportion that equalizes the marginal contributions of core and non-core components to the overall perceived quality. It is a quality-weighted equilibrium point.

Now plug this z into the market absorption constraint $Q_B = y/z \leq 1$, we have,

$$\frac{y}{\theta/(1+\theta)} \leq 1 \Rightarrow y(1+\theta)/\theta \leq 1 \Rightarrow y \leq \frac{\theta}{1+\theta}.$$

To ensure that the assumption is both theoretically sound and practically valid, we empirically validate it using two industry examples: the French wine industry and the Bojiakou Tea Trading Market, shown below.

In the French wine industry, Bordeaux Appellation d'Origine Contrôlée (AOC) wines represent premium core products (quality = 1), while other French wines serve as non-core components (quality $\theta < 1$). Now, we use the empirical data from 2023 to support the model's feasibility assumption $y \leq \frac{\theta}{1+\theta}$, where y denotes the normalized yield of high-quality Bordeaux relative to total French wine production. Specifically, Bordeaux AOC production reached approximately 3.3 million hectolitres (Mhl), compared to France's total wine output of around 36.9 Mhl, yielding $y \approx 3.3/36.9 \approx 0.089$. Using price as a proxy for perceived quality, the average 750 mL bottle price for Bordeaux AOC wines was about €10 in 2023 ($\approx$ \$10.90, with €1 $\approx$ \$1.09) to export, while France's average wine price was $\approx$ \$7.28 per 750 mL bottle. By referencing the export price, we estimate $\theta = \frac{7.28}{10.90} \approx 0.668$, and $\frac{\theta}{1+\theta} = \frac{0.668}{1+0.668} \approx 0.400$. Since $0.089 < 0.400$, the inequality holds, empirically validating the assumption.

Additionally, we employ empirical data from the Bojiakou Tea Trading Market in Rizhao, Shandong Province, China, to further validate the assumption. Although Rizhao has over 20,000 hectares of tea plantations, only about half of Lanshan District's 10,800 hectares qualify as core production areas. Due to stricter pesticide regulations, core-area yields are 90 % of non-core areas. XH's traceability data further reveals that 17.4 % of local fresh leaves were disqualified from core certification due to pesticide issues (e.g., excessive residues). Thus, the yield quantity of the core product can be estimated as $y \approx \frac{10800}{20000} \cdot 0.5 \cdot (1 - 0.174) = 0.22$. As the purchasing cost of fresh leaves from the non-core area is recorded as 46 CNY per kilogram on average, without adding any manufacturing costs (e.g., roasting and labor costs), the material cost per non-core unit is 230 CNY (assuming a 5:1 fresh-to-dry ratio). Therefore, using the average retail price of the core product (657 CNY per kg) as the reference, the lower bound of $\underline{\theta} = \frac{230}{657} \approx 0.35$. Accounting for additional manufacturing costs and profit margins for the non-core product would relax our validation, as $\frac{\theta}{1+\theta}$ increases with θ, and a higher θ provides a less strict condition. Hence, evaluating at $\theta = \underline{\theta} = 0.35$, we have $y = 0.22 < \frac{\underline{\theta}}{1+\underline{\theta}} = \frac{0.35}{1.35} \approx 0.26$, confirming the inequality holds and validating the assumption with real-world yield constraints.

Appendix C. Proofs

Proof of Proposition 1

To solve the maximization problem of

$$\begin{aligned} \max_{p_B, Q_B, z} \pi_B\left(p_B, Q_B, z\right) &= p_B D_B(p_B, z) - c\left(Q_B - y\right), \\ \text{s.t.} \quad Q_B &= \frac{y}{z}, \\ Q_B &= D_B(p_B, z), \end{aligned}$$

we first substitute the objective function based on the Eqs. (3) and (4) as the function of Q. After some rearrangement, the objective function is expressed as the following:

$$\max_{Q_B} c(y - Q_B) + (1 - Q_B)(y + Q_B\theta - y\theta).$$

Taking the first order derivative with regard to Q, we have,

$$\frac{\partial c(y - Q_B) + (1 - Q_B)(y + Q_B\theta - y\theta)}{\partial Q_B} = \theta - (1 - \theta)y - 2Q_B c - c.$$

By solving the first order condition, it gives the $Q_B = \frac{\theta - c - (1-\theta)y}{2\theta}$. Then, by checking the second order condition,

$$\frac{\partial^2\left(c(y - Q_B) + (1 - Q_B)(y + Q_B\theta - y\theta)\right)}{\partial^2 Q_B} = -2\theta < 0.$$

Then, we can confirm the concavity and $Q_B^* = Q_B = \frac{\theta - c - (1-\theta)y}{2\theta}$ is the optimal maximizer.

Plugging Q_B^* back to Eqs. (3) and 4. We get

$$z^* = \frac{2y\theta}{(1+y)\theta - c - y},\ p_B^* = \frac{(\theta + y - \theta y)^2 - c^2}{2[(1+y)\theta - y - c]},\ \pi_B^* = \frac{(c + y + \theta - \theta y)^2}{4\theta} - c(1-y).$$

For the sensitivity of the optimal decisions with regard to the parameters, we have:

$$\frac{\partial p_B^*}{\partial \theta} = \frac{(1-y)^2 + \frac{4(-1+c)y(c+y)}{(c+y-(1+y)\theta)^2}}{2(1+y)} > 0, \quad \text{when} \quad \frac{c + y + 2(1+y)\sqrt{\frac{(1-c)y(c+y)}{(-1+y^2)^2}}}{1+y} < \theta < 1.$$

Otherwise, $\frac{\partial p_B^*}{\partial \theta} < 0$. Thus, p_B^* firstly decreases with θ and then increases with θ.

$$\frac{\partial p_B^*}{\partial c} = \frac{2c(y(1-\theta) - \theta) + (y + \theta - y\theta)^2 - c^2}{2(c + y - (1+y)\theta)^2} > 0.$$

$$\frac{\partial p_B^*}{\partial y} = \frac{(1-\theta)\left(2\left(c(1-y) - y - y^2\right)\theta - (1-y)(3+y) - (c+y)^2\theta^2\right)}{2(c + y - (1+y)\theta)^2} > 0.$$

$$\frac{\partial Q_B^*}{\partial \theta} = \frac{c+y}{2\theta^2} > 0.$$

$$\frac{\partial Q_B^*}{\partial c} = -\frac{1}{2\theta} < 0.$$

$$\frac{\partial Q_B^*}{\partial y} = -\frac{1-\theta}{2\theta} < 0.$$

Since z^* is the reciprocal of Q_B^*, its sensitivity to exogenous variables is the opposite of that of Q_B^*. Therefore, we omit the proof here.

$$\frac{\partial \pi_B^*}{\partial \theta} = \frac{1}{4}\left((1-y)^2 - \frac{(c+y)^2}{\theta^2}\right) > 0,\ \frac{\partial \pi_B^*}{\partial c} = \frac{c + y - (1-y)\theta}{2\theta} < 0.$$

$$\frac{\partial \pi_B^*}{\partial y} = \frac{c + y + (1 + c - 2y)\theta - (1-y)\theta^2}{2\theta} > 0.$$

□

Proof of Lemma 1

We first calculate several critical values of v:

1. Calculate v_1, where the consumer is indifferent between the core and non-core products:

$$v_1 = \frac{p_C - p_N}{1-\theta}$$

2. Calculate v_2, where the consumer is indifferent between the core and not to purchase, and v_3, where the consumer is indifferent between the non-core and not to purchase:

$$v_2 = p_C, \quad v_3 = \frac{p_N}{\theta}$$

Under the reasonable assumption of the non-negativity of D_N^* , we have the following order:

$$v_1 \geq v_2 \geq v_3$$

Consumer Choices by Interval

1. For $v < v_3$:
   (a) $U_C = v - p_C < v_3 - p_C = \frac{p_N}{\theta} - p_C \leq 0$
   (b) $U_N = \theta v - p_N < \theta v_3 - p_N = p_N - p_N = 0$
   (c) Both $U_C \leq 0$ and $U_N \leq 0$.
   (d) Therefore, consumers choose not to purchase (i.e., $U_0 = 0$).
2. For $v_3 \leq v < v_2$:
   (a) $U_C < 0$ (since $v < p_C$).
   (b) $U_N \geq 0$.
   (c) Consumers choose the non-core product.
3. For $v_2 \leq v < v_1$:
   (a) $U_C \geq 0$.
   (b) $U_N \geq 0$.
   (c) We compare U_C and U_N:

$$U_C - U_N = v - p_C - (\theta v - p_N) = (1-\theta)v - (p_C - p_N)$$

For $v < v_1$:

$$(1-\theta)v - (p_C - p_N) < 0$$

Thus, $U_N > U_C$ and consumers choose the non-core product.

4. For $v \geq v_1$:
   (a) $U_C \geq U_N$, so consumers choose the core product.

Demand Functions:
Non-Core Product Demand

$$D_N(p_N) = v_1 - v_3$$

Core Product Demand

$$D_C(p_C) = 1 - v_1$$

Computation of $v_1 - v_3$:
1. Calculate v_1:

$$v_1 = \frac{p_C - p_N}{1-\theta}$$

2. Calculate v_3:

$$v_3 = \frac{p_N}{\theta}$$

3. Compute $D_N(p_N)$:

$$\begin{aligned} D_N(p_N) = v_1 - v_3 &= \frac{p_C - p_N}{1-\theta} - \frac{p_N}{\theta} \\ &= \frac{\theta(p_C - p_N) - (1-\theta)p_N}{\theta(1-\theta)} \\ &= \frac{\theta p_C - \theta p_N - p_N + \theta p_N}{\theta(1-\theta)} \\ &= \frac{\theta p_C - p_N}{\theta(1-\theta)} \end{aligned}$$

4. Compute $D_C(p_C)$:

$$D_C(p_C) = 1 - v_1 = 1 - \frac{p_C - p_N}{1-\theta} = \frac{(1-\theta) - p_C + p_N}{1-\theta}$$

Thus, we have the demand functions:

$$D_N(p_C, p_N) = \frac{\theta p_C - p_N}{\theta(1-\theta)}$$

$$D_C(p_C, p_N) = \frac{1 - \theta - p_C + p_N}{1-\theta}$$

□

Proof of Proposition 2

Since $v > v\theta$, we can conclude that $p_C > p_N$. Thus, the constrain Eq. (8) will always be bounded for higher profit margin. Regarding p_N as a function of p_C, we have

$$p_N(p_C) = p_C + y + \theta - y\theta - 1$$

Plugging into the original objective function, we transfer the objective function as the function of p_C:

$$\max_{p_C} \quad \pi_D\left(p_C\right) = -p_C^2 + p_C(2 + c - 2y - \theta) - (1-y)(c + (1-y)(1-\theta))$$

Taking the first order derivative with regard to p_C, and solve the first order condition of the p_C, we have:

$$p_C^* = \frac{2 + c - 2y - \theta}{2}.$$

And by checking the second order derivative with regard to p_C, we have

$$\frac{\partial^2 \pi_D(p_C)}{\partial^2 p_C} = -\frac{2}{\theta} < 0,$$

which confirms the concavity of the profit function and uniqueness of the maximizer. Substitute the p_C back to $p_N(p_C), D_N(p_C, p_N), \pi_D(p_C, p_N)$, we have

$$p_N^* = \frac{c+\theta-2\theta y}{2}, D_N^* = \frac{\theta - c}{2\theta}, \pi_D^* = (1-y)y - \frac{(\theta-c)^2}{4\theta}.$$

For the sensitivity of the optimal decisions with regard to the parameters, under the condition of $y \in (0, \frac{\theta}{1+\theta})$, we have

$$\frac{\partial p_C^*}{\partial \theta} = -\frac{1}{2} > 0, \quad \frac{\partial p_C^*}{\partial c} = 1/2 > 0, \quad \frac{\partial p_C^*}{\partial y} = -1 < 0.$$

$$\frac{\partial p_N^*}{\partial \theta} = \frac{1}{2} - y > 0, \quad \frac{\partial p_N^*}{\partial c} = \frac{1}{2} > 0, \quad \frac{\partial p_N^*}{\partial y} = -\theta < 0.$$

$$\frac{\partial D_N^*}{\partial \theta} = \frac{c}{2\theta^2} > 0, \quad \frac{\partial D_N^*}{\partial c} = -\frac{1}{2\theta} < 0.$$

$$\frac{\partial \pi_D^*}{\partial \theta} = \frac{1}{4}\left(-1 + \frac{c^2}{\theta^2}\right) < 0, \quad \frac{\partial \pi_D^*}{\partial c} = \frac{-c+\theta}{2\theta} > 0, \quad \frac{\partial \pi_D^*}{\partial y} = 1 - 2y > 0.$$

□

Proof of Corollary 1

To facilitate the comparison, we take the $\frac{p_C^*}{p_N^*} - \frac{1}{\theta}$, and after some rearrangement, we have

$$\frac{p_C^*}{p_N^*} - \frac{1}{\theta} = \frac{\frac{1}{2}(2+c-2y-\theta)}{\frac{1}{2}(c+\theta-2y\theta)} - \frac{1}{\theta} = \frac{(\theta-c)(1-\theta)}{\theta(c+\theta-2y\theta)} > 0.$$

Thereby concluding that $\frac{p_C^*}{p_N^*} > \frac{1}{\theta}$. □

Proof of Proposition 3

For the first part, based on the Proposition 1 and 2, p_B increases with y while p_N decreases with y. Thus, let consider the special case when $y \to 0$.

$$p_B(y=0) - p_N(y=0) = \frac{(c+0(-1+\theta)-\theta)(c+0+\theta-0\cdot\theta)}{2(c+0-(1+0)\theta)} - \frac{1}{2}(c+\theta-2\cdot 0\cdot\theta) = 0$$

Thus, for any $y \in (0, \frac{\theta}{1+\theta}]$, $p_B > p_N$.

In the first part, we prove the gap between the p_B and p_N can be infinitesimally small, and for a given y, $p_C - p_N = (1-y)(1-\theta)$, which is positive even when $y = 0$. Thus, we can concludes that when $y \to 0$, $p_C > p_B$. Additionally, let $\tilde{c}(y)$ solves $p_C = p_B$, and we have

$$\tilde{c}(y) = \frac{((y-2)y) + (2-y)\theta + ((1-y)y-2)\theta^2}{2-y-(2+y)\theta},$$

and for $c > \tilde{c}(y)$, $p_B > p_C$; otherwise, $p_B < p_C$. Furthermore, we take the first order derivative of the $\tilde{c}(y)$ in regard with the y, we have

$$\frac{\partial \tilde{c}(y)}{y} = \frac{\left((-2+y)^2 + (-4+y(4+y))\theta\right)\left(-1+\theta^2\right)}{(-2+y+(2+y)\theta)^2} < 0.$$

Thus, $\tilde{c}(y)$ decreases in y.

Finally, for the last part, since $D_B > y$, it is straightforward to get $D_B > y = D_C$. Also, based on Propositions 1 and 2, and $(1-\theta)y > 0$, so $D_B < D_N$. □

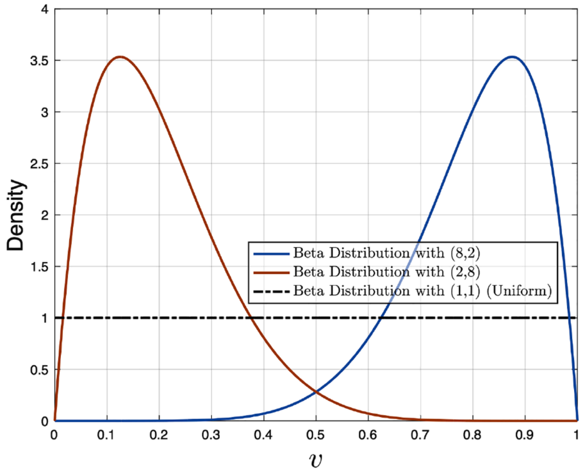

Fig. C.1. Beta distributions.

Proof of Proposition 4

Based on the Propositions 1 and 2, we consider the special case when the difference of the π_B^* and π_D^* is the smallest, with $\theta \to \frac{1}{2}$ while $c \to 0$, and we have

$$G(y) = \pi_D^*(y|\theta = \frac{1}{2}, c = 0) - \pi_B^*(y|\theta = \frac{1}{2}, c = 0) = \frac{1}{8}\left(-2 + 6y - 9y^2\right)$$

The quadratic function $G(y)$'s maximum point is at $y = 0.33$, and $G(y) = -0.125$, which proves that the smallest gap between the π_D^* and π_B^* is negative. Therefore, $\pi_B^* > \pi_D^*$ always holds.

Additionally, we justify the use of the uniform distribution to represent the consumers' willingness to pay and then present robustness tests of our results under skewed distributions.

The assumption of modeling consumers' willingness to pay as follows: a uniform distribution is widely adopted in the operations management literature. Recent studies, such as (Kazaz et al., 2025), assume that consumers are heterogeneous in their willingness to pay for quality, with this heterogeneity uniformly distributed over $[0, 1]$. Similarly, Geng et al. (2022b) and Jiang et al. (2017) also employ a uniform distribution to capture consumers' heterogeneous willingness to pay for quality. Therefore, the assumption of uniformly distributed heterogeneity in willingness to pay is well established in existing research. Moreover, in Hotelling (1929)–the seminal paper introducing the Hotelling model–consumers are assumed to be uniformly distributed along a line segment, where a smaller distance to a store corresponds to a higher willingness to buy, and a larger distance corresponds to a lower willingness to buy.

As the uniform distribution is a special case of the beta distribution with $\alpha = \beta = 1$, the beta distribution is left-skewed when $\alpha > \beta$ and right-skewed when $\alpha < \beta$. Therefore, it is convenient to use the beta distribution to test the robustness. Under the blending strategy, the consumer will purchase the agricultural product only with positive utility. By denoting the cumulative density function of the beta distribution (CDF) as $\mathcal{F}(\cdot)$, the demand under the blending strategy is given by

$$D_B(p_B, z) = \Pr[U_B > 0] = 1 - \mathcal{F}\left(\frac{p_B}{\theta_B(z)}\right).$$

Similarly, under the differentiating strategy, we have

$$D_C(p_C, p_N) = 1 - \mathcal{F}\left(\frac{p_C - p_N}{1 - \theta}\right),\ D_N(p_C, p_N) = \mathcal{F}\left(\frac{p_C - p_N}{1 - \theta}\right) - \mathcal{F}\left(\frac{p_N}{\theta}\right).$$

We also examine the blending dominance with the left-skewed beta distribution $\mathcal{F}_{8,2}(\cdot)$ and the right-skewed beta distribution $\mathcal{F}_{2,8}(\cdot)$. We first display the two distributions along with the uniform special case (Fig. C.1).

When the beta distribution is right-skewed ($\mathcal{F}_{2,8}(\cdot)$), it means most of the consumers are less informed and suffer from ambiguity, which leads to a low willingness to pay. In contrast, the left-skewed ($\mathcal{F}_{8,2}(\cdot)$) distribution indicates that most of the consumers are informed and less affected by the ambiguity in the absence of the blockchain traceability system, which leads to a high willingness to pay. The following figure shows the comparative analysis of retailing strategies without the blockchain traceability system (Fig. C.2).

Numerical results show that the blending dominance robustly exists, indicating that the farmer consistently prefers the blending strategy over the differentiating strategy without the blockchain traceability system. Interestingly, we further find that when the beta distribution is right-skewed, the farmer's profit, under both retailing strategies, is significantly less than the corresponding counterpart under the left-skewed beta distribution. This is because the relatively low willingness to pay from the consumer groups not only depresses the general market demand but also enforces the low retail price under both strategies, thereby limiting the farmer's profitability. Furthermore, we observe that the farmer stops the blending strategy with the right-skewed beta distribution as

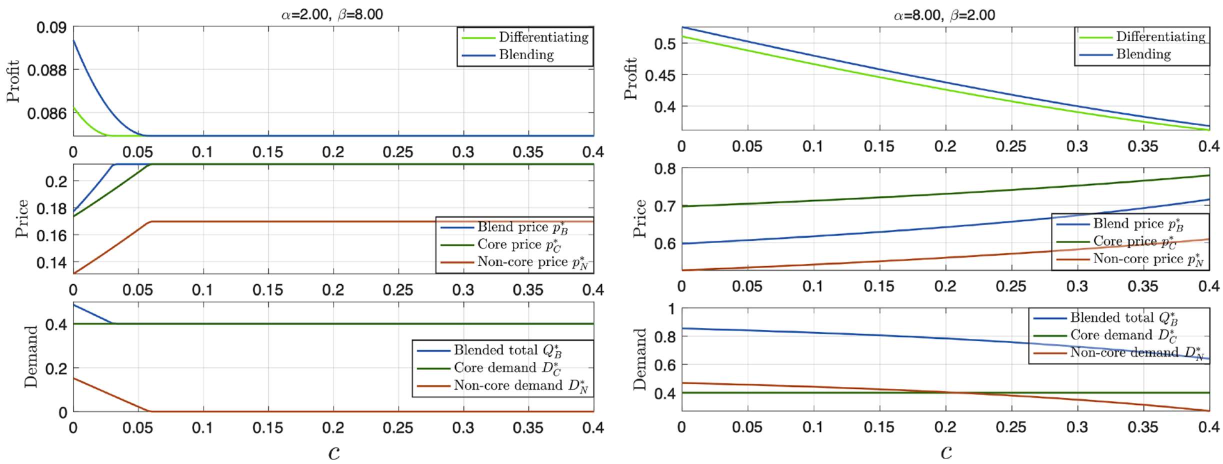

Fig. C.2. Comparative analysis of retailing strategies without blockchain ($\theta = 0.8$, $y = 0.4$).

the purchasing cost c increases. The rationale is that consumers' low willingness to pay does not justify further price increases under the blending strategy. Since the retail price is capped, the farmer chooses to halt procurement in order to reduce costs. However, the farmer always exploits consumers with a higher willingness to pay (i.e., $\mathcal{F}_{8,2}(\cdot)$) to blend the non-core product into the core product. □

Proof of Lemma 2

Consumer Utility Comparison Given the utility functions:

$$U_{C\beta} = 1 - p_{C\beta}, \quad U_{N\beta} = \theta - p_{N\beta}$$

Consumers choose $\mathbb{C}$ if:

$$U_{C\beta} > \max\{U_{N\beta}, 0\}$$

Similarly, they choose $\mathbb{N}$ if:

$$U_{N\beta} > \max\{U_{C\beta}, 0\}$$

Demand for $\mathbb{C}$ ($D_{C\beta}$)
Case 1: $p_{C\beta} \le 1$

$$U_{C\beta} = 1 - p_{C\beta} \ge 0$$

To have $U_{C\beta} > \max\{U_{N\beta}, 0\}$, it suffices that $U_{C\beta} > U_{N\beta}$. Assuming competitive pricing, a fraction y of consumers prefer $\mathbb{C}$ when $p_{C\beta} \le 1$. Thus,

$$D_{C\beta}(p_{C\beta}, p_{N\beta}) = y \quad \text{if } p_{C\beta} \le 1$$

Case 2: $p_{C\beta} > 1$

$$U_{C\beta} = 1 - p_{C\beta} < 0$$

Consumers will not choose $\mathbb{C}$. Hence,

$$D_{C\beta}(p_{C\beta}, p_{N\beta}) = 0 \quad \text{if } p_{C\beta} > 1$$

Combining both cases:

$$D_{C\beta}(p_{C\beta}, p_{N\beta}) = \begin{cases} y, & \text{if } p_{C\beta} \le 1, \\ 0, & \text{if } p_{C\beta} > 1. \end{cases}$$

Demand for $\mathbb{N}$ ($D_{N\beta}$)
Case 1: $p_{N\beta} \le \theta$

$$U_{N\beta} = \theta - p_{N\beta} \ge 0$$

To have $U_{N\beta} > \max\{U_{C\beta}, 0\}$, it suffices that $U_{N\beta} > U_{C\beta}$. Assuming competitive pricing, a fraction $1-y$ of consumers prefer $\mathbb{N}$ when $p_{N\beta} \le \theta$. Thus,

$$D_{N\beta}(p_{C\beta}, p_{N\beta}) = 1 - y \quad \text{if } p_{N\beta} \le \theta$$

Case 2: $p_{N\beta} > \theta$

$$U_{N\beta} = \theta - p_{N\beta} < 0$$

Consumers will not choose $\mathbb{N}$. Hence,

$$D_{N\beta}(p_{C\beta}, p_{N\beta}) = 0 \quad \text{if } p_{N\beta} > \theta$$

Combining both cases:

$$D_{N\beta}(p_{C\beta}, p_{N\beta}) = \begin{cases} 1-y, & \text{if } p_{N\beta} \le \theta, \\ 0, & \text{if } p_{N\beta} > \theta. \end{cases}$$

By evaluating the utility comparisons under different pricing scenarios, we establish that:

$$D_{C\beta}(p_{C\beta}, p_{N\beta}) = \begin{cases} y, & \text{if } p_{C\beta} \le 1, \\ 0, & \text{if } p_{C\beta} > 1, \end{cases}$$

$$D_{N\beta}(p_{C\beta}, p_{N\beta}) = \begin{cases} 1-y, & \text{if } p_{N\beta} \le \theta, \\ 0, & \text{if } p_{N\beta} > \theta. \end{cases}$$

This concludes the proof of Lemma 2. □

Proof of Proposition 5

To maximize $\pi_{D\beta}$, observe that the profit function is linear in both $p_{C\beta}$ and $p_{N\beta}$. Therefore, the maximum profit is achieved at the boundary values of the pricing constraints.

For $p_{CB:}$, to maximize $(p_{C\beta} - b)y$, set $p_{C\beta}$ as high as possible within the feasible region. Hence, set $p^*_{C\beta} = 1$.

For $p_{NB:}$, similarly, to maximize $(p_{N\beta} - c - r)(1-y)$, set $p_{N\beta}$ as high as possible within the feasible region, ensuring $p_{N\beta} \le \theta$. Hence, set $p^*_{N\beta} = \theta$.

Substituting $p^*_{C\beta} = 1$ and $p^*_{N\beta} = \theta$ into the profit function:

$$\pi^*_{D\beta} = (1-b)y + (\theta - c - r)(1-y).$$

Thus, the farmer will always choose the highest reasonable price while serving all the consumers and extracting all the consumer utilities. □

Proof of Proposition 6

Building on the previous proof, we know that, without the blockchain, the farmer's optimal price, p_N, cannot reach the consumers with $v < v_3 = \frac{p_N}{\theta}$. By adopting the blockchain, the farmer can sell to all the consumers who fail to purchase the core product. Thus, $D_{N\beta} > D_N$. Furthermore, under the differentiating strategy (with or without the blockchain traceability system), the farmer always prioritizes the sales of the core product, and clear all the yields. Thus, $D_{C\beta} = D_C$. Finally, we have $D_{N\beta} > D_N > D_B > D_{C\beta} = D_C$.

For the second part, the fulfill rate is the reciprocal of the fulfilled demand over the totoal consumer base. And we already have $D_{N\beta} + D_{C\beta} > D_N + D_C > D_B$, thus $F_{D\beta} > F_D > F_B$. □

Proof of Lemma 3, 4, and Proposition 7

Given the existence of $\tilde{c}(y)$, the price p_C increases linearly with c, while the price p_B increases convexly with c. In contrast, the price $p_{N\beta}$ depends solely on the value of θ and remains constant with respect to c. We define the prices when $c = 0$ as thresholds, specifically $p_C(c=0) = \theta_{C,N\beta}$ and $p_B(c=0) = \theta_{B,N\beta}$, where $\theta_{B,N\beta} < \theta_{C,N\beta}$. Consequently:

For $\theta \in (c, \theta_{B,N\beta})$**:** There are no intersections between $p_{N\beta}$ and either p_B or p_C.
For $\theta \in (\theta_{B,N\beta}, \theta_{C,N\beta})$**:** $p_{N\beta}$ intersects only with p_B and does not intersect with p_C.
For $\theta \in (\theta_{C,N\beta}, 1)$**:**
- There are two intersections between $p_{N\beta}$ and the prices.
- **Exception:** If $\theta > p_C(c = \theta - (1+\theta)y) = \tilde{\theta}_H$, there is only one intersection with p_B and no intersections with p_C.

To facilitate the comparisons, we draw the Figure below to demonstrate the price rankings upon the different levels of the consumer's perceived value, θ (Fig. C.3).

□

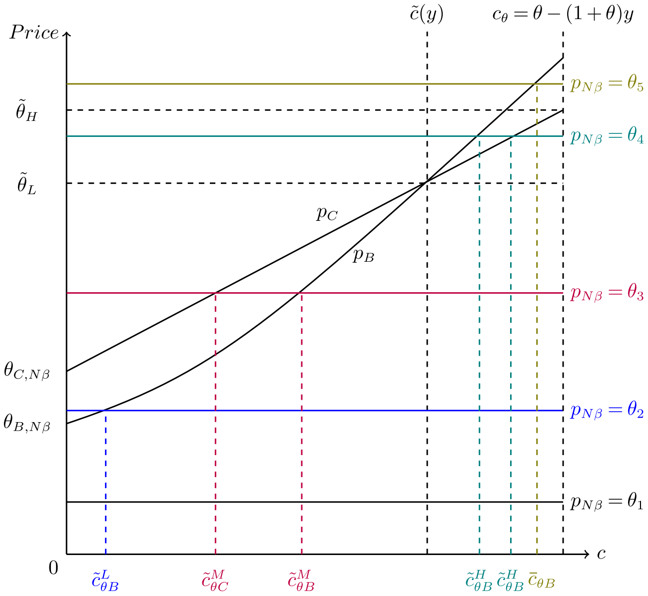

Fig. C.3. Price comparisons with different θ values.

Proof of Proposition 8

Since the $\pi_{D\beta}$ is monotonically decreasing in r, there exists a unique reputation cost threshold, given $y = 0$ and denoted as $\tilde{r}$, that solves $\pi_{D\beta}(y = 0) = \pi_B(y = 0)$, such that for $r < \tilde{r}$, $\pi_{D\beta}(y = 0) > \pi_B(y = 0)$; otherwise, $\pi_{D\beta}(y = 0) < \pi_B(y = 0)$. To explicitly solve the threshold $\tilde{r}$, we have

$$\frac{(c+\theta-\theta y+y)^2}{4\theta} - c(1-y) = (1-b)y + (1-y)(-c+\theta-r),$$

where $r = \frac{(1-b-\theta)y - \frac{(c+\theta-\theta y+y)^2}{4\theta} + \theta}{1-y}$. And with $y = 0$, then $\tilde{r} = \theta - \frac{(c+\theta)^2}{4\theta}$. Additionally, we are able to derive the $\tilde{y}(r) = \max\{\frac{c(\theta-1)-\theta\left(2\sqrt{\frac{\theta\left(b^2+b(\theta-2r-1)+\theta^2-2\theta(r+1)+r(r+3)\right)-c(\theta-1)(b+\theta-r-1)+\theta-r}{\theta}}+2b+\theta-2r-1\right)}{(1-\theta)^2}, 0\}$. Please note that there are two positive solutions of $\tilde{y}(r)$ that solving $\frac{(c+\theta-\theta y+y)^2}{4\theta} - c(1-y) = (1-b)y + (1-y)(-c+\theta-r)$, while the other one is invalid within the core quantity assumption of $y \leq \frac{\theta}{1+\theta}$.

For the second part, given the limited transaction fee rate that the service provider can charge, $\frac{\partial \pi_{D\beta}}{\partial y} = 1 - b + c + r - \theta > 0$. Therefore, both $\pi_{D\beta}$ and π_B increase in y but $\pi_{D\beta}$ decreases in r. For any $y > 0$, the break-even reputation cost threshold, denoted by $\tilde{r}(y)$, is increasing in y. Equivalently, we also can denoted the same trajectory as the function of r, denoted by $\tilde{y}(r)$, such that for $r > \tilde{r}$ and $y < \tilde{y}(r)$, $\pi_{D\beta} < \pi_B$; otherwise, $\pi_{D\beta} > \pi_B$, and $\tilde{y}(r)$ is increasing in r. □

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