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Independent vs. collaborative blockchain Research and Development: Operational decisions in food supply chains

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A B S T R A C T

As blockchain increasingly demonstrates advantages in enhancing consumer trust and reducing collaborative production costs in food supply chains, more food companies are developing blockchain-based supply chain management platforms. However, in a complex and competitive supply chain environment, food companies face critical operational management challenges in selecting appropriate blockchain R&D approaches and determining optimal R&D levels. This study examines two competing food companies deciding on their optimal food production and blockchain R&D levels. We first established a benchmark model without blockchain adoption. Then, we constructed supply chain operation models for both independent and collaborative blockchain R&D scenarios. By comparing equilibrium decisions across different models, we derived the optimal blockchain R&D model and operational strategies in food supply chains. Furthermore, we extended our analysis to consider asymmetric food substitution scenarios. Our findings revealed that independent blockchain R&D tends to increase equilibrium food production and is more suitable for premium food supply chains. Conversely, collaborative blockchain R&D significantly enhanced overall supply chain profitability. As spillover effects increase, food companies are likely to favor independent blockchain R&D to achieve higher R&D levels and stronger market competitiveness. Additionally, we demonstrated that blockchain R&D levels are influenced by food substitutability and quality credibility.

A R T I C L E I N F O

Keywords:
Blockchain adoption;
Food supply chains;
Game theory;
Competitive collaboration;
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1. Introduction

With the increasing popularity and advancement of blockchain technology, stakeholders in the food supply chain have begun to recognize its value. Food manufacturers, retailers, and blockchain firms are actively engaging in blockchain R&D aimed at enhancing the management and oversight of information across various stages of food production, processing, storage, transportation, and distribution. The primary objective of these initiatives is to establish a decentralized, tamper-proof, and transparent system that improves the integrity and efficiency of the food supply chain.

The benefits of blockchain for the food supply chain are increasingly apparent. For consumers, the adoption of blockchain by food companies enhances engagement by showcasing robust food safety systems, improving brand perception, and fostering confidence in product quality. This increased transparency can stimulate consumer demand by allowing individuals to make more informed purchasing decisions. For food companies, a blockchain network facilitates collaboration between upstream and downstream stakeholders within the supply chain. A distributed ledger maintains comprehensive information on food raw materials, production, processing, storage, logistics, supplier transfers, and retail operations, thereby enabling mutual oversight. Enhanced information sharing across different stages allows companies to quickly assess overall supply chain performance, improve operational efficiency, and make informed decisions while minimizing communication costs. For example, “Blockchain + Vegetables” innovation project in Weifang City, where the Yukesong Digital Agriculture Industry Park developed a digital agricultural management platform that integrates vegetable planting, logistics, storage, processing, and sales. This initiative not only enhanced the quality of agricultural products within the park but also achieved over a 10 % reduction in water and fertilizer usage and a labor cost reduction exceeding 15 %.

Additionally, blockchain R&D has certain positive externalities that can bring multiple benefits to the blockchain industry and society. Firstly, blockchain R&D can promote innovation and advancement in blockchain technology, improving its functionality, performance, and security, thus bringing more value and benefits to the blockchain industry and society. Secondly, it can drive the standardization and normalization of blockchain technology, reducing R&D and operational costs and risks, enhancing credibility and interoperability, and thereby bringing more order and vitality to the blockchain ecosystem and food market. Thirdly, it can facilitate the integration and expansion of blockchain technology with other emerging information technologies such as 5G, IoT, and AI, creating an innovative "Blockchain +" model that supports the food industry in exploring new business operation models and management solutions.

Given the numerous advantages of blockchain, many food companies have begun to invest in blockchain R&D. Common approaches include: (1) Independent R&D, where some food companies choose to develop or customize blockchain solutions to meet their specific business needs. The advantage of independent R&D is that it allows for tailored blockchain solutions based on distinct requirements and scenarios, thereby improving system flexibility and adaptability. However, it requires significant investments in human, material, and financial resources and presents challenges related to immature technology and a lack of standards. (2) Collaborative R&D, where some food companies choose to develop and utilize blockchain solutions in partnership with other organizations to facilitate cross-organization data sharing and collaboration. For instance, global food retailers such as Walmart and Nestlé have partnered with IBM to develop a blockchain-based service system, establishing a global food safety alliance aimed at enhancing the efficiency and transparency of the food supply chain. The advantage of collaborative R&D lies in leveraging the technology and resources of partners, which reduces development and operational costs and risks while increasing system credibility and interoperability. However, it necessitates the coordination of interests and the resolution of issues related to data privacy and security.

Moreover, the R&D costs represent a major obstacle for food companies in adopting blockchain services. For example, in terms of software, blockchain adoption requires selecting or developing an appropriate blockchain platform, writing smart contracts, and integrating data verification functions. This process necessitates substantial investments in human, material, and financial resources while facing challenges related to immature technology and a lack of standardization. Additionally, blockchain solutions must integrate with the existing systems of brand owners, addressing discrepancies in system architecture, data standards, and data exchange protocols, which adds to the complexity and overall cost of R&D. In terms of hardware, blockchain solutions need to be deployed on servers, networks, and storage devices, requiring investments in equipment, physical space, and considerations of performance, security, and stability. Furthermore, the adoption of blockchain solutions necessitates the use of coding and reading devices for processing food information, which involves purchasing or leasing the necessary equipment while considering factors such as cost, efficiency, and compatibility. This paper explores the issues related to the supply chain operation management of food companies in the context of blockchain R&D and discusses the following questions:

(1) In the highly competitive food industry, what motivates members of the food supply chain to conduct blockchain R&D? Additionally, how does blockchain impact operational decisions within the food supply chain?
(2) When comparing blockchain independent R&D to collaborative R&D, which model is more advantageous for operational decisions? Furthermore, how do operational decisions in the food supply chain differ between two R&D scenarios?

(3) In a more complex food market environment (e.g., the asymmetric substitute foods), will the choice of blockchain R&D model change?

To the best of our knowledge, this paper is one of the pioneering analytical operations managements (OM) studies that explore operational decision-making strategies related to blockchain R&D, providing theoretical insights for food companies in selecting appropriate blockchain R&D models. Addressing the issue of poor information communication within food supply chains, we comprehensively consider the advantages of blockchain platforms in enhancing operational efficiency and reducing production costs. We conduct a comparative analysis of the operational decision-making differences between independent and collaborative R&D blockchain platform models and propose optimal choices for blockchain R&D models at different stages of development.

We organize the paper as follows. Section 2 provides a comprehensive review of related studies to identify gaps in the literature and appropriately position our contribution. In Section 3, we define the problem, outline its assumptions, and develop the model. Section 4 analyzes the value of blockchain R&D in the food supply chain. Section 5 further explores operational decisions for food supply chains under different Blockchain R&D models based on the context of asymmetric substitute foods and provide targeted management insights.

2. Literature review

2.1 Blockchain in supply chains

Numerous investigations have explored the potential advantages of distributed ledger technology for various sectors and enterprises within supply chain ecosystems [1, 2]. The implementation of this innovative technology in supply chain operations management is becoming increasingly prevalent. For instance, it has been applied to enhance supply chain transparency and verify product authenticity [3-6]. Furthermore, it has demonstrated its capacity to promote supply chain sustainability [7-9] and even revolutionize lean manufacturing practices within supply chains [10, 11]. Notably, the body of research examining the integration of distributed ledger technology with food supply chain management continues to expand rapidly.

The application of distributed ledger systems in supply chain management has seen a significant surge in interest. Numerous researchers have employed diverse methodologies to investigate the potential implementation of this technology in supply chain operations. For instance, Wu *et al.* took an analytical approach to examine strategies for adopting a distributed ledger technology system (DLTS) in fresh product supply chains (FPSC). They compared scenarios without this technology to three different situations where various FPSC members led the DLTS implementation. Their research yielded optimal conditions for DLTS deployment in FPSC and proposed a two-part tariff contract to coordinate DLTS construction [12]. Bumblauskas *et al.* utilized a case study approach to investigate the deployment of this technology in egg distribution. Their findings demonstrated how it can enhance accuracy and transparency in product movement throughout supply chains [13]. Kamble *et al.* adopted a hybrid methodology, combining Interpretive Structural Modeling and Decision-Making Trial and Evaluation Laboratory, to explore strategies for implementing distributed ledger systems in agricultural supply chains, with a focus on ensuring food safety and sustainability [14]. Wang *et al.* has examined blockchain's impact on pricing strategies in dual-channel supply chains, revealing how this technology incentivizes dynamic pricing adjustments across sales periods while accounting for strategic consumer behavior [15].

As the advantages of distributed ledger technology become increasingly apparent, researchers have begun to delve into specific operational challenges within this framework. For instance, Mangla *et al.* utilized system dynamics modeling to examine the implementation of distributed ledger technology in a sustainable dairy supply chain. This study showcased how technology could be leveraged to address sustainability concerns in a complex, perishable goods supply chain [16]. In the context of food supply networks, Rogerson and Parry employed case study methodologies to empirically demonstrate the capacity of distributed ledger systems to enhance supply chain visibility. Their research highlighted the transformative potential of this technology in improving transparency across the entire supply chain [17]. Taking a different approach, Behnke and Janssen conducted an empirical investigation into the requisite modifications of supply chain organizational structures and the importance of persuading supply chain participants to dismantle information silos [18]. Yang and Zhang proposed a blockchain-based production scheduling and control optimization (PSCO-PC) strategy for intelligent manufacturing. By introducing adaptive difficulty mechanisms and improving simulation model flexibility, the research addressed data throughput and consensus challenges. Experimental results validated the strategy's effectiveness in optimizing production resource control and enhancing matching rationality in manufacturing systems [19] .

Existing studies have explored blockchain technology adoption in various supply chains, primarily using methods like case analyses, empirical research, and interpretive structural modeling. However, game-theoretic analytical approaches remain scarce in this area. Our study differs by comparing operational decision-making between independent and collaborative blockchain R&D approaches. We also suggest optimal blockchain R&D strategies for different developmental stages. By comparing independent and collaborative blockchain R&D models, we provide theoretical insights that guide food companies in their strategic decision-making. Our analysis considers various factors, including food substitutability, quality credibility, and spillover effects, to determine optimal R&D levels and production strategies. This holistic approach allows us to propose tailored solutions for different supply chain scenarios, contributing to the overall effectiveness of food supply chains in an increasingly competitive landscape.

2.2 Competitive collaboration in supply chain

Research on competitive collaboration in supply chains has also gained significant attention. Various studies have explored different aspects of this phenomenon. For instance, an investigation into e-commerce channels examined optimal decisions and profits for online retailers and manufacturers across four service channel types, highlighting revenue sharing as a crucial factor [20]. In the fresh produce sector, a study on supplier competition revealed that freshness preservation efforts and retailer's information disclosure level significantly influence supply channel dynamics [21]. Another research focused on a manufacturer's service selection between competing module suppliers, suggesting that leveraging diverse pricing and service strategies from both suppliers could be more beneficial than relying on a single superior supplier [22]. The timing of pricing and marketing decisions in manufacturer-led supply chains has also been analyzed. Through a series of game-theoretic models, researchers identified optimal decision timing by comparing equilibrium outcomes across different supply chain configurations [23]. Furthermore, Deng employed machine learning-enhanced agent-based modeling to examine retailer price competition under consumer learning behavior and supplier competition. The study utilized fuzzy logic, genetic algorithms, reinforcement learning, and swarm intelligence to simulate market dynamics. Results showed that different consumer learning behaviors lead to varied retailer competition patterns, while supplier price competition affects the intensity of retailer price competition. The study provides a simulated market model for future research on price competition among supply chain actors [24].

In the context of blockchain application, Liu *et al*. investigated blockchain service provision in supply chains with downstream competition. Using game theory, they analyzed the optimal strategies for a manufacturer and two competing retailers. Their work explored how blockchain impacts market dynamics, economic outcomes, and service performance in competitive supply chain settings. These studies underscore the potential of blockchain to reshape competitive collaboration in modern supply chains [25]. Similarly, Song *et al*. examined how blockchain affects information sharing decisions among rival e-commerce sellers. Their research on a two-competitor market revealed that blockchain adoption becomes universal when consumer trust in information is low or implementation costs are minimal. This highlights how blockchain can foster collaboration even in competitive environments [26]. Yan *et al*. compared blockchain-based and traditional approaches to supply chain information coordination. They developed a three-level supply chain model incorporating retailer information sensitivity. Their study revealed that blockchain technology can effectively reduce operating costs. Interestingly, they found that moderate levels of information-sensitive retailers optimize blockchain value, as extreme levels may increase privacy concerns among supply chain companies [27].

Our research builds upon previous studies by offering a comprehensive analysis of blockchain's role in food supply chains, focusing on operational efficiency and production costs. Unlike earlier work that primarily examined competitive dynamics and information disclosure, we investigate the critical choice between independent and collaborative blockchain R&D approaches. This study addresses the unique challenges in food supply chains, such as consumer trust and collaborative production costs.

3. The model

This paper considers the operational decision-making issues of two food companies in the context of a duopoly market. Food companies i $(i = 1, 2)$ each sell similar types of food with a certain degree of substitutability. As blockchain technology begins to be applied in various food segments, both companies are aware that blockchain R&D can enhance market demand potential, increase consumer trust in food quality, and reduce food production costs. The food production and sales price of company are denoted as q_i and p_i, respectively, while the blockchain R&D effort is denoted as s_i, the higher intensity of blockchain R&D, the more production costs the company can save, and consumer trust in the food will also increase. To improve the readability, Table 1 summarizes all abbreviations and definitions of important variables involved.

Table 1 Notation used in this paper

Notation	Definition
q_i	Production of food company i
s_i	The blockchain R&D effort level(the level of blockchain services)
p_i	The sales price of food company i
π_i	The profit of food company i
Q	Total production of the food supply chain
θ	Market demand potential under blockchain adoption
α	Market demand potential without blockchain adoption
β	Food substitutability coefficient
c	Unit production cost of food companies without blockchain adoption
C_i	Total production cost of food companies with blockchain adoption
γ	The coefficient of blockchain R&D spillover effect
x	Food quality
t	The credibility of food's quality

3.1 Without considering blockchain R&D

As the benchmark model, we first consider the scenario where blockchain technology is conducted in the food supply chain. Without considering the blockchain R&D, the two food companies do not engage in collaborative R&D. Followed the previous studies [28-31], the respective inverse demand functions of can be expressed as follows:

$$p_i^{NN} = \alpha - q_i^{NN} - \beta q_{3-i}^{NN} + xt \tag{1}$$

where α represents the market demand potential without blockchain technology. The market demand potential is normalized to 1 $(\alpha = 1)$. This assumption is consistent with the research hypothesis of Niu et al. (2021) and does not affect the main results. β represents the food substitutability coefficient $(0 < \beta < 1)$; x denotes the food quality. Premium food typically refers to products of superior quality, high nutritional value, and fine processing, such as organic or imported foods. Ordinary food refers to products of average quality and lower processing levels, like everyday groceries; t represents consumer trust in food quality $(0 \le t < 1)$. When $t = 0$, it indicates that consumers have no trust in the information described on food packaging and completely distrust the stated food quality. In this case, only consumers who are entirely insensitive to food quality will choose to purchase, deciding solely based on price. Clearly, as consumer trust in food quality increases, they will be willing to pay a higher price for the food. In the blockchain context, t also reflects consumer adoption of verification tools - higher t implies not only greater trust but also more consumers actively using blockchain verification, which directly enhances the market value of blockchain investment.

The profit functions for the two food companies can be expressed as follows:

$$\pi_i^{NN} = p_i^{NN} q_i - c q_i^{NN} = (\alpha - q_i^{NN} - \beta q_{3-i}^{NN} + xt - c) q_i^{NN} \tag{2}$$

where c represents the unit production cost of food ($0 < c < \alpha + xt$). Under equilibrium conditions, the optimal quantity for each food company and the total production of the food supply chain can be expressed as:

$$q_i^{NN*} = \frac{1 + tx - c}{2 + \beta} \tag{3}$$

$$Q^{NN*} = \frac{2(1 + tx - c)}{2 + \beta} \tag{4}$$

The optimal profit for each food company can be expressed as:

$$\pi_i^{NN*} = \frac{(1 - c + tx)^2}{(2 + \beta)^2} \tag{5}$$

3.2 Independent blockchain R&D

When both food companies decide to develop blockchain services, firstly, the addition of blockchain technology to food products will attract more consumers, thereby increasing the potential demand for such products in the market. Secondly, because information about the entire process from production to distribution will be recorded and verified in their respective blockchain services, consumer trust in the quality and safety of the food will be strengthened. Additionally, the reduction in food production waste and improvement in production efficiency will lower the production costs for the companies. Therefore, when food companies choose to conduct blockchain R&D independently, the following applies:

$$p_i^{NB} = \theta - q_i^{NB} - \beta q_{3-i}^{NB} + x(t + s_i^{NB}) \tag{6}$$

$$C^{NB} = \left(c - s_i^{NB} - \gamma s_{3-i}^{NB}\right) q_i^{NB} \tag{7}$$

$$\pi_i^{NB} = p_i^{NB} q_i^{NB} - C^{NB} - \frac{{s_i^{NB}}^2}{2} \tag{8}$$

In the above formula, γ represents the spillover effect of blockchain R&D ($0 < \gamma < 1$). As an innovation activity that enhances production efficiency, the blockchain R&D may have positive spillover effects on other companies in the market that undertake similar R&D actions. For the production process, blockchain technology greatly ensures the credibility and security of food production and distribution data, and the adoption of blockchain can reduce the data verification and audit costs for both parties involved in the transaction. For the transaction process, if both food companies use smart contract features of blockchain technology to simplify and automate market transactions, the risk of transaction defaults and time costs will decrease.

From an industry development perspective, blockchain R&D by any food company will drive the digital transformation of the entire industry supply chain, promoting improvements in production efficiency across the industry. Therefore, it can be inferred that the external effects of a food company's R&D activities will lower the unit production costs of its competitors.

It is also worth noting that, in practice, regulatory and data-sharing constraints significantly influence the magnitude of spillover effects. In regions with relaxed regulatory environments, inter-firm technology exchange and data sharing are more convenient, resulting in relatively higher γ values. However, in jurisdictions with strict data protection regulations, information sharing between companies faces more legal restrictions, leading to lower γ values. Thus, γ reflects not only technological knowledge diffusion but also the impact of institutional environments on collaborative R&D feasibility.

Additionally, the relationship between R&D expenditure and returns is modeled using a quadratic function to reflect the diminishing returns of R&D investment. Thus, given s_i^{NB}, the equilibrium production quantities for the two food companies can be expressed as:

$$\begin{cases} q_1^{NB}(s_1^{NB},s_2^{NB})^* = \frac{\theta+tx-c}{2+\beta} + \frac{s_1^{NB}(2+2x-\beta\gamma)}{4-\beta^2} + \frac{s_2^{NB}(2\gamma-\beta-x\beta)}{4-\beta^2} \\ q_2^{NB}(s_1^{NB},s_2^{NB})^* = \frac{\theta+tx-c}{2+\beta} + \frac{s_1^{NB}(2\gamma-\beta-x\beta)}{4-\beta^2} + \frac{s_2^{NB}(2+2x-\beta\gamma)}{4-\beta^2} \end{cases} \tag{9}$$

Based on this, the total market demand for food in the production phase can be expressed as:

$$\begin{aligned} Q^{NB}(s_1^{NB},s_2^{NB})^* &= \frac{2\theta+tx-c}{2+\beta} + \frac{s_1^{NB}(2-\beta)(1+x+\gamma)}{4-\beta^2} + \frac{s_2^{NB}(2-\beta)(1+x+\gamma)}{4-\beta^2} \\ &= \frac{2R}{2+\beta} + \frac{Y}{2+\beta}\cdot 2s_i^{NB} \end{aligned} \tag{10}$$

For simplicity in the formula, let $Y = 1 + x + \gamma$, which can be understood as the positive impact of the R&D spillover effect on the level of R&D; let $R = \theta + tx - c$, which can be understood as the marginal revenue per unit of food. In the expression for total food market demand in the production phase, the first term $2R/(2+\beta)$ represents the sum of the equilibrium quantities of the two food companies without R&D; the second term $Y/(2+\beta)$ represents the positive impact factor of R&D level on total demand. The numerator reflects the impact of the R&D spillover effect, with a larger γ indicating a stronger spillover effect and thereby increasing total demand. The denominator β reflects the sensitivity of market demand to food substitutability, with a larger β indicating more intense market homogenization and thus reducing total demand.

By substituting $q_1^{NB}(s_1^{NB},s_2^{NB})^*$and $q_2^{NB}(s_1^{NB},s_2^{NB})^*$ into π_1^{NB} and π_2^{NB}, and calculating the second derivative of the profit expressions for the two food companies, it can be determined that maximum profit occurs when $(2+2x-\beta\gamma)/(4-\beta^2) < \sqrt{2}/2$. Thus, the optimal R&D level for food companies under independent blockchain R&D is:

$$s_i^{NB^*} = \frac{2NR}{BB' - 2NY} \tag{11}$$

where $N = 2 + 2x - \beta\gamma$, which can be understood as the negative impact of the R&D spillover effect on the level of R&D; NY can represent the complementarity between the R&D levels of the two companies. When the R&D spillover effect γ is large, this value is smaller, indicating that the R&D levels of the two companies mutually enhance each other, thus increasing total demand. When γ is small, this value is larger, indicating that the R&D levels of the two companies counteract each other, thus reducing total demand; $B = 4 - \beta^2$, $B' = 2 + \beta$, and $B \cdot B'$ can be understood as the negative impact of food substitutability on the level of R&D.

Under independent blockchain R&D model, the optimal food production quantities for each food company and the total food production can be expressed as:

$$q_i^{NB^*} = \frac{BR}{BB' - 2NY} \tag{12}$$

$$Q^{NB^*} = \frac{2BR}{BB' - 2NY} \tag{13}$$

The optimal profit for each food company can be expressed as:

$$\pi_i^{NB} = \frac{R^2(B^2 - 2N^2)}{(BB' - 2NY)^2} \tag{14}$$

3.3 Collaborative blockchain R&D

This model examines the scenario in which two food companies engage in collaborative efforts during the blockchain R&D phase. When these companies opt for cooperative R&D initiatives, the extent and sophistication of blockchain R&D are collectively determined through the combined efforts and resources of both companies, so $s^{CRB} = s_1^{CRB} = s_2^{CRB}$.

First, using the same calculation methods as in the previous section, we calculate the optimal profit for each food company. Accordingly, under blockchain R&D collaboration, the joint profit function for the two food companies can be expressed as:

$$\pi^{CRB} = \pi_1^{CRB} + \pi_2^{CRB} \tag{15}$$

Accordingly, in the production phase, given s^{CRB}, the equilibrium production quantities for the two food companies can be expressed as:

$$q_i^{CRB}(s^{CRB})^* = \frac{R + Ys^{CRB}}{2+\beta} = \frac{2R}{2+\beta} + \frac{Y}{2+\beta} \cdot 2s_i^{NB} \tag{16}$$

When $Y/(2+\beta) < 1/\sqrt{2}$, the food companies achieve maximum profit. Thus, the optimal R&D level for the two food companies under independent blockchain R&D is:

$$s^{CRB^*} = \frac{2RY}{B'^2 - 2Y^2} \tag{17}$$

$$q_i^{CRB^*} = \frac{RB'}{B'^2 - 2Y^2} \tag{18}$$

$$\pi_i^{CRB^*} = \frac{R^2}{B'^2 - 2Y^2} \tag{19}$$

4. The value of blockchain R&D in food supply chain

By comparing the equilibrium quantities under three scenarios—no blockchain adoption, independent blockchain R&D, and collaborative blockchain R&D, the following conclusions can be drawn:

Proposition 1: (1) $q_i^{NN^*} < q_i^{NB^*}$， $q_i^{NN^*} < q_i^{CRB^*}$; (2) when $2\gamma - (1+x)\beta > 0$, then $q_i^{NB^*} < q_i^{CRB^*}$; when $2\gamma - (1+x)\beta < 0$，then $q_i^{NB^*} > q_i^{CRB^*}$.

Proposition 1 indicates that (1) The food supply chain can improve its optimal production quantity by conducting blockchain R&D. (2) The impact of the blockchain R&D model on the equilibrium production quantity of the food supply chain is influenced jointly by the blockchain R&D spillover effect (γ), food quality (x), and food substitutability (β).

To illustrate the findings of Proposition 1 more clearly, we perform calculations with assigned values for the relevant variables. Assume $\theta = 1.2$, $c = 0.8$, $t = 0.9$. The effect of variations in γ, x, and β within their respective ranges on the difference in food supply chain production quantities is shown in Fig. 1.

Firstly, by comparing the feasible region where $q_i^{CRB^*} > q_i^{NB^*}$, it is observed that the independent R&D model is more likely to achieve higher equilibrium food production quantities compared to the collaborative R&D model.

Secondly, as food quality increases, the region where collaborative R&D blockchain can achieve higher food production quantities becomes increasingly constrained. This suggests that high-quality food is typically a key product for food companies with high commercial value. If the two food companies collaborate on blockchain R&D, the sales data and flow information of high-quality food are likely to be acquired by competitors, leading to a gradual reduction in their optimal production quantity. However, if the two food companies develop blockchain R&D independently, each can maintain its own data and information, better protect its commercial secrets and competitive advantage, and adjust its production and sales strategies more flexibly to meet consumer demands and preferences, thereby increasing its market share.

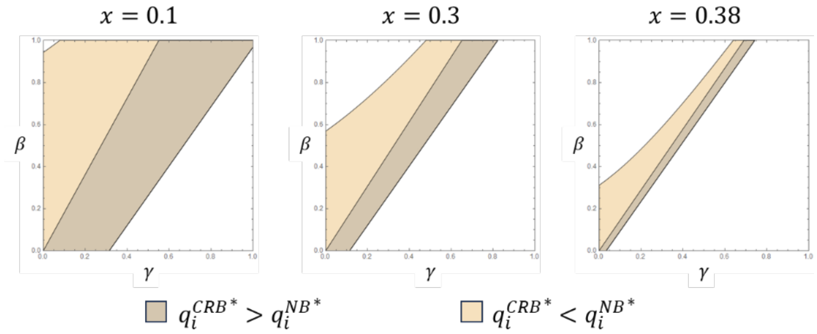

Fig. 1 Evolution of the dominant region between $q_i^{NB^*}$ and $q_i^{CRB^*}$

Proposition 2: (1) when $\theta > \theta'$, $\pi_i^{NN^*} < \pi_i^{NB^*}$; (2) when $\theta < \theta'$, $\pi_i^{NN^*} > \pi_i^{NB^*}$; (2) $\pi_i^{NN^*} < \pi_i^{CRB^*}$, $\pi_i^{NB^*} < \pi_i^{CRB^*}$.

Proposition 2 indicates that the adoption of blockchain does not necessarily lead to profit increases for members of the food supply chain. When food companies choose to independently conduct blockchain R&D, it is only more profitable for food companies to opt for independent blockchain R&D if the blockchain significantly enhances the potential demand for the food supply chain. Assuming $x = 0.2$ and keeping the other parameters constant, Fig. 2 illustrates the range of profit differences between choosing to develop and not to conduct blockchain R&D in the food supply chain.

It can be observed that, firstly, under different settings of potential market demand for food, the area where $\pi_i^{NN^*} < \pi_i^{NB^*}$ is always larger than the area where $\pi_i^{NN^*} > \pi_i^{NB^*}$. This suggests that, although there are instances where not conducting blockchain R&D yields higher profits, choosing independent R&D is more likely to result in greater economic benefits. Secondly, as the blockchain increases the potential market demand for food, represented by θ, the feasible area for $\pi_i^{NN^*} < \pi_i^{NB^*}$ expands accordingly, indicating that the economic incentive for food companies to conduct blockchain R&D also strengthens. While our model treats consumer trust t as a constant parameter, in reality, trust in blockchain systems can be undermined by misinformation or security breaches. Such trust erosion would effectively reduce t, thereby raising the profitability threshold θ in Proposition 2. This means even greater market demand enhancement would be required to justify blockchain investment. For instance, a security breach that reduces t could shift a company from the profitable region (where $\pi_i^{NN^*} < \pi_i^{NB^*}$) to the unprofitable region, highlighting why maintaining blockchain integrity is crucial for sustained profitability.

However, if food companies choose to collaborate on blockchain R&D, the profit level of the food supply chain can be significantly enhanced compared to the other two blockchain development models mentioned above. Thus, choosing collaborative R&D is a more economically viable operational strategy.

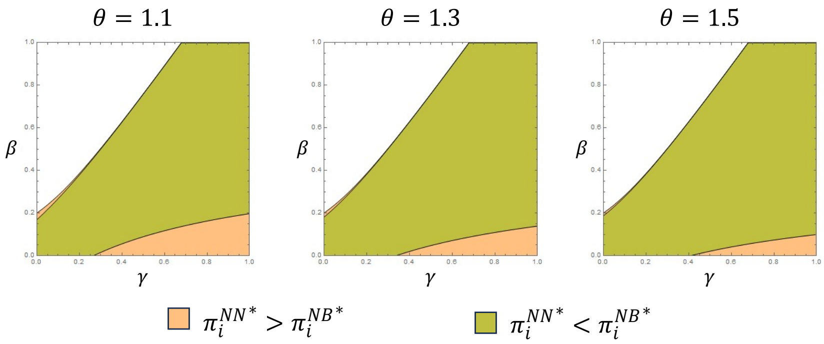

Fig. 2 Evolution of the dominant region between $\pi_i^{NN^*}$ and $\pi_i^{NB^*}$

Proposition 3: (1) when $\gamma < \frac{(1+x)\beta}{2}$, $s_i^{CRB^*} > s_i^{NB^*}$; (2) when $\gamma > \frac{(1+x)\beta}{2}$, $s_i^{CRB^*} < s_i^{NB^*}$.

Proposition 3 indicates that when the spillover effect level of blockchain R&D is below a certain threshold, a collaborative R&D model enables the food supply chain to achieve a higher level of R&D effort. Conversely, when the spillover effect level is higher, an independent R&D model can achieve a higher level of R&D effort. Specifically, when the blockchain R&D spillover effect is relatively low, it implies that the application of blockchain technology is not yet widespread and deep enough. In such cases, deeper integration with other technologies like the IoT, big data, and AI is required, which increases the complexity and cost of technology development and maintenance. If a company opts for a collaborative R&D model, it can coordinate and integrate the technical resources and advantages of other companies within the supply chain, thus reducing the difficulty and risk of technology development and maintenance. This approach can help achieve a higher level of blockchain R&D in the food supply chain. On the other hand, when the blockchain R&D spillover effect level is high, it indicates that blockchain technology is already quite mature and stable. In such a scenario, food companies can customize the blockchain services according to the specific characteristics of their supply chain, achieving a higher level of blockchain service application. This not only helps to protect their trade secrets and competitive advantages but also enhances their market competitiveness.

Fig. 3 illustrates the variation in the difference between the level of blockchain collaborative R&D and independent R&D under different levels of R&D spillover effects. As γ increases, the feasible region where the collaborative R&D model achieves a higher R&D level gradually expands and moves towards the upper left region of the graph. This suggests that when the spillover effect of R&D is low, food companies lack sufficient motivation and resources to engage in R&D collaboration. However, as the spillover effect of R&D increases, the production efficiency of food companies is significantly enhanced with the help of blockchain services, prompting them to have a stronger incentive to engage in collaborative R&D and improve the level of blockchain services. On the other hand, this move may also intensify competition in the food market (as shown in the graph by the increase in the food substitutability rate, β). Furthermore, implementation time lags in blockchain deployment create additional strategic considerations, as early collaborative investors must balance the immediate costs against delayed spillover benefits, potentially moderating the attractiveness of collaboration even in high-spillover environments.

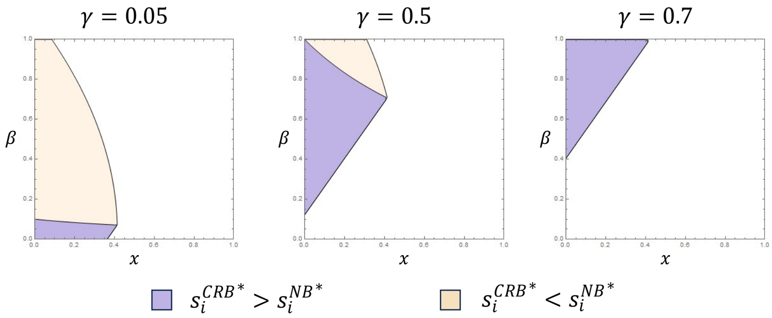

Fig. 3 Evolution of the dominant region between $s_i^{CRB^*}$ and $s_i^{NB^*}$

5. Extended analysis

5.1 Asymmetric substitute foods

This section expands the research background to include asymmetric substitute food supply chains, considering supply chain operational decisions within the more complex context of blockchain R&D collaboration. Asymmetric substitute foods refer to cases in the food market where two or more types of food exist, and their substitutability is not mutual but rather one-directional. For example, soy milk can serve as a substitute for cow's milk, catering to the needs of individuals who are lactose intolerant or follow a vegetarian diet. However, cow's milk cannot completely replace the nutritional value and health benefits of soy milk. Based on these industry observations, this subsection assumes that the food product of Company 1 is superior to that of Company 2. Thus, the former can be considered a perfect substitute for the latter, but not vice versa. In the remaining content of this subsection, the product of Company 1 will be referred to as the "superior food", while the product of Company 2 will be referred to as the "inferior food". To simplify the modeling process, this subsection assumes that β_2=1 and β_1=β<1. Therefore, under independent R&D, the inverse demand function for the food supply chain can be rewritten as follows:

$$p_1^{ANB} = \theta - q_1^{ANB} - \beta q_2^{ANB} + x(t + s_1^{ANB}) \quad (20)$$

$$p_2^{ANB} = \theta - q_2^{ANB} - q_1^{ANB} + x(t + s_2^{ANB}) \quad (21)$$

Furthermore, under collaborative R&D, the inverse demand function for the food supply chain can be rewritten as follows:

$$p_1^{ACB} = \theta - q_1^{ACB} - \beta q_2^{ACB} + x(t + s_1^{ACB}) \quad (22)$$

$$p_2^{ACB} = \theta - q_2^{ACB} - q_1^{ACB} + x(t + s_2^{ACB}) \quad (23)$$

Referring to similar calculation steps from the previous text, the equilibrium decision results for the two food companies in the asymmetric substitute food supply chain, under both independent and collaborative blockchain R&D scenarios, can be easily derived.

5.2 Comparison of R&D levels in asymmetric substitute food companies

By comparing the equilibrium R&D levels of asymmetric substitute food companies under independent blockchain R&D model, the following conclusions can be drawn:

Proposition 4: when $\beta > 4(\sqrt{2} - 1 - x)/(\sqrt{2} - 2\gamma)$ or $\beta < 4(\sqrt{2} - 1 - x)/(\sqrt{2} - 2\gamma)$ and $3\sqrt{2} + 2\gamma \geq 4 + 4x$, $s_1^{ANB^*} < s_2^{ANB^*}$; Otherwise $s_1^{ANB^*} > s_2^{ANB^*}$.

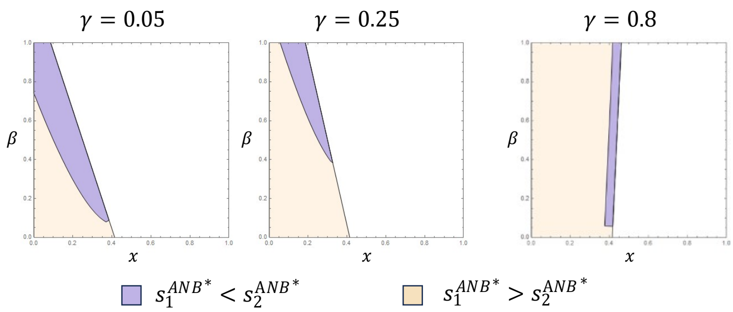

Fig. 4 Evolution of the dominant region between $s_1^{ANB^*}$ and $s_2^{ANB^*}$

Proposition 4 indicates that the relative sizes of food quality levels, food substitutability rates, and blockchain R&D spillover effects collectively determine the R&D levels of the two food companies. When R&D spillover effects are low, the inferior food company may have a higher R&D level than the superior food company under lower market competition or higher food quality levels. This suggests that, under lower market competition, superior food companies may lack the motivation to invest in blockchain R&D, as they already hold a significant market share. In contrast, inferior food companies need to invest in blockchain R&D to enhance their market position and increase their revenue and profit. At higher food quality levels, superior food companies already possess high quality and reputation, so there is less need to invest in blockchain services to further enhance their brand image. Meanwhile, inferior food companies need to use blockchain services to demonstrate that their products are also of high quality and reliability, thereby attracting more high-end consumers.

Using the same parameter settings as in the previous subsection, and setting γ to $\gamma = 0.05, 0.25, 0.8$ respectively, Fig. 4 illustrates the comparative results of R&D levels for asymmetric substitute food companies under independent blockchain R&D. The figure shows that, under various R&D spillover parameter settings, the feasible domain where $s_1^{ANB^*} > s_2^{ANB^*}$ is significantly larger than the domain where $s_1^{ANB^*} < s_2^{ANB^*}$. This indicates that superior food companies are more likely to set higher blockchain R&D levels to maintain their dominant position in the market.

5.3 Value of R&D collaboration for asymmetric substitute food supply chains

By comparing the optimal production quantities and optimal profits of the two food companies in the context of independent blockchain R&D for asymmetric substitute foods, the following conclusions can be drawn:

Proposition 5: (1) $Q^{ANB^*} < Q^{ACB^*}$; (2) $\pi^{ANB^*} < \pi^{ACB^*}$.
Proposition 5 indicates that in an asymmetric substitute food supply chain, collaborative blockchain R&D can lead to higher overall consumer demand and total profit in the food market. Comparing this with the conclusions from Proposition 1, it is evident that, when food substitutability is asymmetric, the food production under collaborative R&D will be strictly higher than under independent R&D.

For members of the food supply chain, this asymmetric substitutability means that the impact of collaborative R&D on blockchain services differs between companies. For Company 1, collaborative R&D can enhance the advantages of its food products, thereby consolidating its market leadership, capturing a larger market share, and increasing its profit levels. For Company 2, collaborative R&D can help compensate for the disadvantages of its food products, thereby improving its market competitiveness, attracting more consumers, and boosting its profit levels.

6. Conclusion

This paper explores the blockchain R&D decision-making issues faced by food companies in the context of the increasing application of blockchain technology in food supply chain management. It focuses on two competing food companies simultaneously developing blockchain services on their self-built blockchain platforms. The paper examines the motivations for developing blockchain services, the impact of blockchain services on supply chain operational decisions, differences in supply chain operational decisions under independent and collaborative R&D models, and changes in R&D model choices in more complex food market environments (such as asymmetric substitute foods). To address these issues, the paper establishes several models: Supply chain operational decisions without blockchain R&D collaboration (Benchmark Model), supply chain operational decisions with collaborative blockchain R&D (Collaborative R&D Model), and supply chain operational decisions under the context of asymmetric substitute foods (Asymmetric Substitute Foods Model).

By comparing optimal operational decisions for food companies under three models—no blockchain R&D, independent R&D, and collaborative R&D—the paper derives the optimal model and operational strategy for blockchain R&D collaboration in food supply chains. Additionally, the paper revisits operational decision schemes under different R&D models in the context of asymmetric substitute foods to test the robustness of the benchmark model results and provide more targeted management insights:

From the perspective of food supply chain production, (1) Independent blockchain R&D tends to achieve higher market equilibrium production compared to collaborative R&D. This is because independent R&D better protects food companies' trade secrets and competitive advantages, whereas collaborative R&D may lead to information leakage and imitation by competitors. (2) High-value premium food supply chains are more suited for independent blockchain R&D, while ordinary food supply chains are better suited for collaborative R&D. Premium foods have higher commercial value and competitive advantages, giving supply chain members a stronger incentive and ability to protect their trade secrets and intellectual property, thus reducing the risk of information leakage and imitation. Ordinary foods, being more homogeneous, benefit more from collaboration to reduce R&D costs and risks.

From the perspective of food supply chain profit: The application of blockchain does not necessarily increase profits for food supply chain members. For independent R&D, it is only profitable when the blockchain's potential demand enhancement effect reaches a certain level. For collaborative R&D, the profit level of the food supply chain can be significantly higher compared to the other two blockchain R&D models. Therefore, choosing collaborative R&D is a more economical operational strategy.

From the perspective of blockchain R&D, both independent and collaborative model of blockchain R&D can achieve relatively higher equilibrium R&D levels. The level of blockchain R&D spillover effects reflects the stage of blockchain service application in the food market. When blockchain technology is not yet widely and deeply applied, the R&D spillover effect level is lower, making collaborative R&D a better choice. As the adoption of blockchain and R&D progress, the spillover effect level increases, and food companies will gradually shift towards independent R&D model to achieve higher levels of blockchain service and stronger market competitiveness. Additionally, when considering further asymmetric food R&D contexts, it is found that the R&D levels of blockchain under independent and collaborative models are also influenced by the level of food differentiation and food quality. Inferior goods may set higher R&D levels in independent R&D to prove their food quality and attributes to consumers.

We propose several avenues for future research. First, exploring how consumer trust in blockchain affects the adoption of independent versus collaborative R&D models could provide valuable insights into strategic decision-making in food supply chains. Second, future studies should investigate the role of blockchain R&D in enhancing sustainability practices within food supply chains, particularly regarding transparency and traceability. Lastly, examining the long-term impact of blockchain R&D on competitive advantage will be crucial as companies transition from collaborative to independent models in response to market dynamics.

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