Front. Eng. Manag. 2023, 10(1): 107–120
https://doi.org/10.1007/s42524-022-0232-2

RESEARCH ARTICLE

Xiutian SHI, Siru CHEN, Xiaofan LAI

Blockchain adoption or contingent sourcing? Advancing food supply chain resilience in the post-pandemic era

Abstract In the post-pandemic era, food supply chains and firms therein are facing unprecedented severe challenges, because once infection is detected, numerous products must be recalled or abandoned, and both suppliers and retailers in the supply chain suffer enormous loss. To survive under the pandemic, retailers have adopted different sourcing strategies, such as contingent sourcing, which, in turn, affect the upstream suppliers and hence the resilience of the whole supply chain. With the rapid development of digital technologies, retailers nowadays can utilize blockchain as a reliable and efficient way to reduce product risk and hence advance the resilience of food supply chains by improving product traceability and inspection accuracy, and making sourcing transparent. In this paper, we develop a game-theoretic model to investigate the interrelation between the retailer's decisions on blockchain adoption and sourcing strategies. We consider that a retailer originally orders from a risky supplier while conducting an imperfect inspection to detect infected products before selling. The retailer may speculatively keep on ordering from the risky supplier or adopt contingent sourcing by ordering from an alternative safe supplier. The retailer also has an option to implement blockchain to improve the inspection accuracy and product traceability. We derive the optimal retail prices under different sourcing strategies with and without blockchain adoption and then analyze the incentives for sourcing strategy and blockchain adoption. Then, we identify the conditions of an all-win situation for food retailer, supplier, supply chain resilience, and consumers with/without government subsidy. Finally, we extend to consider the situation that some consumers have health-safety concerns and preferences for blockchain adoption.

Keywords food supply chain, blockchain, contingent sourcing, supply chain resilience

Received June 30, 2022; accepted September 7, 2022

Xiutian SHI, Siru CHEN
School of Economics and Management, Nanjing University of Science and Technology, Nanjing 210094, China

Xiaofan LAI (✉)
Institute of Big Data Intelligent Management and Decision, College of Management, Shenzhen University, Shenzhen 518060, China
E-mail: xiaofanlai@gmail.com

This work was supported in part by the National Natural Science Foundation of China (Grant Nos. 72071113 and 71701222), Excellent Applied Research Program of Jiangsu Provincial Federation of Philosophy and Social Sciences (Grant No. 22SYB-098), Humanities and Social Science Fund of Ministry of Education of China (Grant No. 21YJC630052), Guangdong Basic and Applied Basic Research Foundation (Grant No. 2023A1515030260), Social Sciences and Planning Fund of Shenzhen (Grant No. SZ2022C009), Stable Support Plan Program of Shenzhen Natural Science Fund (Grant No. 20200812134420001), and SZU-LU Joint Research Programme (Grant No. 202202003).

1 Introduction

1.1 Background and motivation

All types of business operation have been challenged by the COVID-19 outbreak, especially in the food industries. According to McKinsey's report, consumers and governments have serious health-safety concerns about the source area and cold chain logistics, where the virus is able to survive for extended periods (McKinsey, 2020). Their responses to infected products, once detected, often lead to dramatic effects on retailers and suppliers along the food supply chains. For instance, Fresh Hema, a giant retailer owned by Alibaba, has been affected by sporadic outbreaks of the pandemic. Several workers were infected, and some stores were involved during the epidemiological survey for infected consumers in 2021. As a result, Fresh Hema conducted extensive tests for a total of 9989 samples collected from 12 affiliated warehouses and processing facilities at substantial testing costs (Yang et al., 2021).

Food suppliers have also crucially suffered from the pandemic. Following the discovery of the virus on imported salmon, a surge in COVID-19 cases was connected to a massive wholesale food market in Beijing. Although China's Center for Disease Control declared that no evidence shows that salmon was the host for the virus, the outbreak sparked a salmon panic in China, where supermarkets and restaurants hurried to pull salmon from shelves and imports from Europe were significantly suspended. Academic research has shown that the resilience capacity of supply chains, especially adaptive and contingent sourcing from backup suppliers, helps supply chain members withstand disruptions (Hosseini et al., 2019). It resonates with practices in food industries during the COVID-19 pandemic. Retailers have turned to ordering chilled and frozen salmon from countries such as Chile and the Faroe Islands, where the virus was not rampant at that time. The alternative purchasing excluding European suppliers leads to a dramatic reduction in the export sales of salmon. According to the statistics offered by Her Majesty's Revenue and Customs, the total exports of Scottish salmon fell by 23% in 2020, and the sales were down by 76% in China and 42% in the US.

Incurring substantial costs after unsafe food product detection is the main reason behind the retailers' switches of sourcing channels. Unless supported by evidence or traceability to the source of the unsafe product, retailers have to pay a large amount of penalty, typically a fine, and conduct product recalls with suppliers when the infection/unsafe product is detected by the market of regulators (Jin et al., 2021). According to a report by Food Marketing Institute and Consumer Brands Association, the average large claim of a food product recall is usually around $10 million, whereas companies surveyed claimed $30 million per incident under COVID-19, which puts food product supply chains at a disruption risk (Felix et al., 2020). The incentive-based approach, by charging high penalty cost for infection, is efficient in urging retailers to purchase from safe sources, even with high extra emergency costs. Note that changing suppliers also has a negative effect. As aforementioned, the original suppliers suffer from abrupt order cancellations and stranded food, which leave many of them with excess stock that they cannot easily redirect/resell to consumers. Conversely, alternatively ordering single-sourced products from safe suppliers incurs emergency costs, which further threatens the retailers' profit margin and even catalyzes bankruptcies, as the margins among prices logistics and transaction costs are already narrow during the pandemic (Felix et al., 2022). Pier 1 Imports, a famous home goods retailer, declared bankruptcy and ceased operations in 2020. According to its bankruptcy filing, its mass-market merchandizing strategy is based on high-volume, low-price, and lower-margin commodity items, which fails to resonate with customers with health-safety concerns and can no longer help Pier 1 survive at premium ordering costs with safety commitment. To achieve supply chain resilience in the "new normal" after COVID-19, food product retailers are motivated to adopt new technologies for traceability, reliable/trustworthy information, and improving the efficiency of inspection.

In food industries, blockchain has been proposed by pioneers to improve visibility and provide traceable information with full trust (Rogerson and Parry, 2020; Choi and Shi, 2022b). Supported by a decentralized system, reliable data/information can be shared with relevant parties with traceability after adopting blockchain. Once infected products are detected, identifying and taking appropriate actions become easy. As a result, blockchain helps companies, especially those in food industries, demonstrate their credentials in ethical sourcing and ensure that they navigate through challenging times and achieve supply chain resilience (Sharma et al., 2020). For example, food retailers can provide proof of origin credentials and detect infected goods with speed and accuracy by creating "source to shelf" solutions based on blockchain. Supported by high technology, the food product journey can be traced when it moves through a supply chain (PwC, 2020). IBM Food Trust, a collaborative network of growers, processors, wholesalers, distributors, and retailers, enhances accountability and enables visibility across the food supply chain, cutting the time needed to track a food source from days to seconds. It is worthy to note that the tracking provenance of food supplies and their status mitigates the spread of contamination and prevents the waste in the case of a foodborne illness outbreak. Fernandez (2021) further supported that blockchain-based IBM Food Trust creates significant savings in reduced waste by precisely tracking the source of contaminated/infected products. It also reduces food companies' exposure to risk by validating food sources and tracking cold chains from farms or sea to the end consumers. Although blockchain adoption has been widely observed in the food industries, its benefits and challenges under the epidemic are not yet systematically explored in the academic field with the consideration of different sourcing strategies.

1.2 Research questions and contributions

Motivated by the challenges faced by food supply chains under the COVID-19 outbreak, as well as probable solutions, we conduct an analytical analysis to explore the following research questions:

(1) For a food product retailer, what are the optimal pricing decisions and sourcing strategies with and without blockchain implementation?

(2) Is it always efficient to conduct contingent sourcing from a backup supplier based on inspections? When will the adoption of blockchain benefit the food supply chain, and how does it substitute for contingent sourcing?

(3) When will the adoption of blockchain benefit the retailer, food supplier, supply chain resilience, and

consumers at the same time? What should the government do to reach an all-win situation?

To address the aforementioned research questions, we study the sourcing strategies and incentives for blockchain adoption of a food product retailer, who originally sources from a supplier with potential infection risks. The infected food product, once detected by the market, incurs substantial penalty cost to the retailer. In the absence of blockchain adoption, the food retailer has three sourcing options: Sticking to sourcing from a risky supplier, alternatively sourcing from a safe supplier at premium ordering costs, or choosing the sourcing strategy based on the result of an inspection, which is not perfect. After adopting blockchain, the inspection becomes more precise, and the retailer is also benefited from efficient product traceability enabled by the high technology. By theoretically deriving the optimal sourcing strategy and pricing policies, we investigate the retailer's incentive for blockchain implementation and related implications. For the optimal sourcing strategy, choosing contingent sourcing is not always beneficial for the retailer due to the high extra emergency cost. Blockchain plays a role in substituting contingent sourcing by offering traceable products and improving the inspection accuracy; however, it is not always effective either. Essentially, blockchain adoption is an outcome of the trade-off among its operations cost, extra emergency cost, and the possible penalty cost due to infection. In addition, blockchain helps enhance the retailer's continuous operations by guaranteeing profits while improving the supply resilience when the retailer keeps ordering from the risky supplier. From the consumers' perspective, although blockchain adoption raises the retail price, the consumer surplus is higher with this technology, particularly when conducting contingent sourcing is more expensive compared with maintaining blockchain operations. Then, we analytically identify when implementing blockchain can achieve an all-win situation for the food retailer, supplier, and consumers. If the condition for an all-win situation is not satisfied, then the government may play a coordinating role by adopting a "carrot and stick" policy to the retailer. That is, it is urged to offer subsidy for blockchain adoption when the retailer orders from the original supplier and charge an additional penalty cost for the detection of infected food products. Finally, we further analyze a scenario where some consumers have health-safety concerns and preferences for blockchain adoption, which strengthens the retailer's incentives for the high technology, amplifies the benefit of blockchain on consumer surplus, and becomes easier to reach an all-win situation.

1.3 Organization

The remainder of this paper is organized as follows. After reviewing the related literature in Section 2, we first propose the model setting and then show some preliminary results in Section 3. The retailer's optimal sourcing strategy and incentive for blockchain adoption are investigated in Section 4. In Section 5, we explore when implementing blockchain can achieve an all-win situation. When it fails to do so, we further propose how the government should response to help and coordinate. In Section 6, we extend the model by considering consumers' food health-safety concerns and preferences for blockchain adoption. We conclude in Section 7 with discussions on future research directions.

2 Literature review

This paper is related to two streams of research. The first aspect is on food supply chain management with safety concerns, especially in the context of adopting blockchain technologies in industries. The second stream focuses on supply chain resilience under disruptions. We review them one by one as follows.

2.1 Food supply chain management and operations

There exists an abundant literature on food supply chain management with quality consideration in terms of empirical or case-based studies. On the basis of a conceptual framework, six key elements of a safe supply chain were developed by Roth et al. (2008), namely, traceability, transparency, testability, time, trust, and training. Although inspection, such as sampling technology, is an acceptable solution when managing the supply chain quality and risk, it is imperfect (Chen et al., 2014). To address the adulteration risk, Babich and Tang (2012) further analytically showed that the inspection mechanism cannot eliminate suppliers' adulteration, whereas a deferred payment mechanism can. However, they did not recommend selecting the combination of the deferred payment and inspection mechanisms, which leads to redundancy. In addition to inspection mechanism, studies on traceability in food supply chains are also related to our research. On the basis of the accuracy of traceability, Piramuthu et al. (2013) examined the recall dynamics in a perishable supply network and the allocation of liability among different players. Yao and Zhu (2020) explored the role of traceability and market inspection in combating product label misconduct by developing a game-theoretic model. They indicated that the adoption of a traceable product label system may backfire without a proper management mechanism in place. As food safety problem has been exacerbated by the COVID-19 outbreak (Blackmon et al., 2021), relevant research starts to shed a spotlight on the value of technologies, such as bar code, Quick Response (QR) code, and Radio Frequency Identification (RFID), in food supply chains, regarding the impact factors of traceability system construction.

Among these high technologies, blockchain has been widely used in food industries to address traceability problems (Zhao et al., 2019; Rogerson and Parry, 2020; Li et al., 2021; Choi and Shi, 2022b). Casino et al. (2021) indicated that the implementation of blockchain plays a crucial role in establishing a secure food traceability system. Vu et al. (2021) first provided a systematic literature review on blockchain adoption in food supply chains and then proposed a step-by-step conceptual framework for blockchain implementation. Wu et al. (2021) evaluated blockchain adoption in the fresh product supply chain. They showed that the value of adopting blockchain depends on three factors: The consumers' acceptance for food products without blockchain, the deterioration rate of the product, and the allocation proportion of traceability cost for blockchain implementation. Shi et al. (2021) presented cases and observations of food platforms and suppliers who adopt blockchain technologies to foster consumers' trust during COVID-19. Yang et al. (2021) established a game-theoretic model to study the decision of linking information nodes on blockchain along a food supply chain. After investigating an all-win situation, they also discussed which prevalent contracts can achieve supply chain coordination in the presence of blockchain. In view of blockchain characteristics and applications in food supply chains, our work highlights that adopting blockchain technologies benefits the retailer and consumers based on traceability and accurate inspection.

More recently, Liu et al. (2022) examined the value of blockchain on an imported fresh food supply chain consisting of an imported manufacturer, a retailer, and a blockchain platform during COVID-19 pandemic. They found that the blockchain may not always have great benefits to the whole supply chain, and derived the conditions for an all-win situation. Dong et al. (2022) discussed the impact of blockchain-driven traceability technology on a general three-tier food supply chain network that has multiple tier-2 suppliers. They found that the supply chain network structure affects the benefit distribution of blockchain adoption. However, these studies do not consider different types of sourcing strategies for the retailer. Therefore, the interrelation between the blockchain adoption and sourcing strategies has not been explored. Our work enriches the existing research by considering the substitution effect of blockchain adoption and sourcing strategies, which has significant impacts on supply chain resilience under the epidemic.

2.2 Supply chain resilience under disruptions

Supply chain resilience becomes increasingly important under COVID-19 which leads to supply disruptions. A stream of literature has investigated how to manage disruptions in supply chain management (Tao et al., 2020). Early studies have indicated that enhancing supply chain resilience is an efficient approach to deal with disruptions (Ponomarov and Holcomb, 2009). Against the background of the epidemic, recent research has focused on the effects of supply networks (Ivanov and Dolgui, 2020), innovative business models (Choi, 2020), risk management (El Baz and Ruel, 2021), logistics systems and management (Singh et al., 2021), and contract design (Choi and Shi, 2022a) on supply chain resilience against disruption risk. Hosseini et al. (2019) conducted a comprehensive review of literature on quantitative modeling the supply chain resilience. They stated that enhancing the adaptive capacity, such as alternative sourcing from backup suppliers, is a proactive strategy that makes supply chain more resilient and helps firms survive under supply disruptions.

A stream of studies has investigated how sourcing strategies mitigate supply chain disruption risks and achieve resilience. Hu and Kostamis (2015) conducted an approximate model to derive the optimal sourcing strategies when some but not all suppliers face supply disruption risks. He et al. (2020) examined the impact of sourcing decision on mitigating supply disruption and recall risks. They showed that single sourcing is optimal with low recall risk and disruption probability; conversely, dual sourcing is optimal when the disruption probability is moderate or high. In view of supply disruption, price, capacity, and quality, Firouz et al. (2017) investigated the supplier selection problem of a firm offering a single product via multiple warehouses. Wang and Yu (2020) studied the relationship between contingent sourcing and responsive pricing, which is influenced by the emergency cost and potential lost sales in resisting supply chain disruption risks. Similar to the aforementioned studies, this paper also demonstrates the value of sourcing strategies on supply chain resilience with the consideration of disruption risks. However, different from them, derive values of blockchain deployment are also explored in this paper. As Choi et al. (2019), Sharma et al. (2020), and Shi et al. (2021) stated, blockchain-based technologies drive supply chains to become more resilient by simplifying ethical sourcing and providing transparency. Focused on dealing with the COVID-19 outbreak for food supply chains, this article analytically compares the values and effects of sourcing strategies and blockchain implementation.

3 Model preliminaries

3.1 Sourcing strategies without blockchain

A food retailer (he) originally orders from a supplier (she) with potential infection risks under the COVID-19 epidemic. The supplier can be either safe (denoted as u) or risky (denoted as r) with respective probabilities of $1-e_s$ and e_s, where $e_s \in (0, 1)$. Let Y represent the supplier's type, where $Y = u$ or r. A safe supplier has negligible infection risk, as she sources from a safe area where no infection has been reported. Products ordered from a risky supplier are potentially infected at a probability η $(0 < \eta < 1)$, which is equivalent to the proportion of infected products in an ordering batch. Note that the infected product will be detected in the market and recalled by the retailer eventually. Once the infected food problem is exposed by the market, the retailer incurs an additional penalty cost K, which combines the compensation, brand damage, and penalty charged by regulators (Plambeck and Taylor, 2016; Yang et al., 2021). Note that a sufficiently high penalty cost (K) will result in nonpositive profit to the retailer, who would cease operations, leading to the disruption along the supply chain.

The retailer conducts an inspection, such as food quality and infection tests, to counter infection risk in advance and maintain supply chain resilience accordingly. On the basis of the inspection result, the retailer can observe a private signal X about the type of supplier in advance, where $X = R$ if infections are detected, and $X = U$ otherwise. The signals R and U are received before selling and conditionally independent given the supplier type. As shown in Fig. 1, if the supplier is safe and credible, then the retailer cannot find any infected products (i.e., $\text{Prob}\{X = R \mid Y = u\} = 0$). When ordering from a risky supplier, the retailer can detect with probability $\text{Prob}\{X = R \mid Y = r\} = e_r$, which represents the inspection accuracy (Chen et al., 2019). Note that a risky supplier passes the retailer's detection by a fluke with probability of $\text{Prob}\{X = U \mid Y = r\} = 1 - e_r$. The retailer updates his belief about the supplier's type and makes ordering

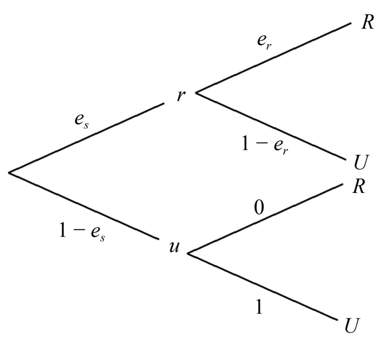

Fig. 1 Model of supplier's type, infected risk, and inspection efficiency.

decisions after the inspection. Given the detection accuracy (e_r) and the prior probabilities of supplier's type (e_s and $1 - e_s$), the probabilities of inspection results and the retailer's updated belief are presented in Table 1.

On the basis of the updated belief of the supplier's type, the retailer selects a sourcing strategy accordingly. For concreteness, he may stick to purchasing from the original supplier or alternatively choose a risk-free backup supplier as contingent sourcing.

It is widely observed that the backup supplier serves other retailers at the same time, and can charge an extra emergency cost per unit product, which is denoted as Δ (Wang and Yu, 2020). Then, we assume that the retailer orders the product from the original (emergency) supplier at a wholesale price w $(w + \Delta)$ per unit and sells to the market at a retail price p per unit. For simplification, we consider a negligible wholesale price of the original supplier by letting $w = 0$, which is robust to the main results in this work. We index the original supplier and the emergency backup supplier as O and A, respectively, for expositional ease.

The retailer selects a sourcing strategy from three candidates, namely, (O, O), (A, A), and (O, A), given the updated belief about the supplier type (U, R). Under Strategy (O, O), the retailer speculatively orders from the original supplier regardless of the inspection result. On the contrary, the retailer always switches to the alternative supplier for safety concerns under Strategy (A, A). Under Strategy (O, A), the retailer orders from the original supplier when receiving signal U from the inspection, which indicates that no infected product is found; while he conducts the contingent sourcing if the signal is R, which implies that infections are detected through inspection. Note that a rational retailer will not consider Strategy (A, O), which is opposite to Strategy (O, A) and dominated by other strategies (i.e., (O, O), (A, A), and (O, A)). Therefore, we neglect Strategy (A, O).

We consider a group of homogenous consumers who are sensitive to the retail price in the basic model. Then, the utility of these consumers is $u = v - p$, where $v \in (0, 1)$ is the uniformly distributed product valuation. Without loss of generality, the market size is normalized as 1. The retailer's expected profits under Strategies (O, O), (A, A), and (O, A) are as follows:

$$\pi_{O,O}^{R,N} = p\left[(1 - e_s)(1 - p) + e_s(1 - p)(1 - \eta)\right] - e_s \eta K, \quad (1)$$

Table 1 Probability of inspection result and retailer's updated belief

Probability of inspection result	Retailer's updated belief of supplier's type
$\text{Prob}\{X = R\} = e_s e_r$	$\text{Prob}\{Y = r \mid X = R\} = 1$
	$\text{Prob}\{Y = u \mid X = R\} = 0$
$\text{Prob}\{X = U\} = 1 - e_s + e_s(1 - e_r)$	$\text{Prob}\{Y = r \mid X = U\} = \dfrac{e_s(1 - e_r)}{1 - e_s + e_s(1 - e_r)}$
	$\text{Prob}\{Y = u \mid X = U\} = \dfrac{1 - e_s}{1 - e_s + e_s(1 - e_r)}$

$$\pi^{R,N}_{A,A} = (p-\Delta)(1-p), \quad (2)$$

$$\pi^{R,N}_{O,A} = e_s e_r (p-\Delta)(1-p) + [1-e_s+e_s(1-e_r)] \cdot \left[\frac{e_s(1-e_r)[p(1-p)(1-\eta)-\eta K]}{1-e_s+e_s(1-e_r)} + \frac{(1-e_s)p(1-p)}{1-e_s+e_s(1-e_r)}\right], \quad (3)$$

where the superscript R, N represents the retailer's profit without blockchain adoption, and the subscripts denote sourcing strategies. The additional penalty cost K is undertaken by the retailer with probability η under Strategies (O, O) and (O, A) when the risky products enter the market and cause food problems after passing his inspection coincidentally. For Eq. (3), the first term represents the expected profit obtained by sourcing from the alternative supplier when receiving signal R, whereas the second term is the expected profit by sourcing from the risky supplier with signal U under Strategy (O, A). With likelihood $1-e_s+e_s(1-e_r)$, signal U indicates two outcomes, that is, the infected product passes the inspection accidently and the batch of product is safe, the conditional probability of which is shown in Table 1.

Sourcing strategies have significant effects on supply chain resilience. For instance, the retailer has to cease business under Strategy (O, O) due to a high penalty cost (i.e., $\pi^{R,N}_{O,O} < 0$, $K > p(1-p)(1-e_s\eta)/e_s\eta$); while the risky supplier's business is unaffected under Strategy (O, O), as the retailer always orders from her and undertakes all the penalties. However, the supplier loses the selling opportunity at probabilities 1 and $e_s e_r$ under Strategies (A, A) and (O, A), respectively. Without loss of generality, we assume that the risky supplier can match other retailers in the market and stay in business at probability ξ, whereas she loses the market and ends operations at probability $1-\xi$. To capture the supplier's viability during the pandemic in the absence of blockchain, we denote β^N_j as the probability of the supplier's continuous operations, where j represents the sourcing strategy adopted by the retailer (i.e., $\beta^N_{O,O} = 1$, $\beta^N_{A,A} = \xi$, and $\beta^N_{O,A} = 1-(1-\xi)e_s e_r$).

3.2 Sourcing strategies with blockchain

In the presence of blockchain adoption, the inspection accuracy is significantly improved, i.e., scanning RFID tags reduces negligence and the inspection record stored in blockchain is permanent and reliable (Choi and Shi, 2022b). To conduct a tractable analysis, we assume that the retailer is able to identify the supplier's type precisely with blockchain by letting $e_r = 1$. As product traceability can be achieved after implementing blockchain, once the supplier is labeled as risky, the retailer conducts an inspection of the orders and can detect the infected products, the proportion of which is η by efficiently tracking the sourcing information. Note that the infected products are returned without charging any cost.

Under Strategy (O, O), the retailer always orders from the original supplier with potential risk, but he can identify the unreliable products and return to the upstream. Under Strategy (A, A), blockchain adoption has no influence on operations yet incurs additional costs. Hence, it is dominated by the strategy in the scenario without blockchain. Under Strategy (O, A), the retailer chooses the corresponding supplier after obtaining the true type of the original one. Without loss of generality, the fixed and variable costs for blockchain implementation and maintenance are captured by T_b and c_b, respectively. Although the variable maintaining cost of blockchain adoption is notable, variable operations cost is also reduced by this technology. Hence, the variable costs of blockchain maintenance are not extremely high. Let superscript B denote the scenario where blockchain is adopted. The expected profits under different sourcing strategies are presented as follows:

$$\pi^{R,B}_{O,O} = (p-c_b)[(1-e_s)(1-p)+e_s(1-p)(1-\eta)] - T_b, \quad (4)$$

$$\pi^{R,B}_{A,A} = (p-c_b-\Delta)(1-p) - T_b, \quad (5)$$

$$\pi^{R,B}_{O,A} = e_s(p-c_b-\Delta)(1-p) + (1-e_s)(p-c_b)(1-p) - T_b. \quad (6)$$

Note that the infected product, if any, is detected by the retailer through efficient tracing function due to blockchain adoption before flowing into the end market. Accordingly, the penalty cost (K) can be avoided under the scenario where blockchain is adopted. Then, due to the safe sourcing guaranteed by blockchain features, the retailer always survives once he adopts this high technology (i.e., $\pi^{R,B}_j \geqslant 0$, $\forall j \in \{(O,O), (O,A), (A,A)\}$). For the supplier, we use β^B_j to capture her viability during the pandemic in the presence of blockchain, where $\beta^B_{O,O} = 1$, $\beta^B_{A,A} = \xi$, and $\beta^B_{O,A} = 1-(1-\xi)e_s$.

3.3 Optimal operation decisions and performance

It can be shown that the profit is concave in retail price under each sourcing strategy without/with blockchain adoption. We use superscript i and subscript j to represent the blockchain adoption and sourcing strategies, respectively, where $i \in \{N, B\}$, and $j \in \{(O,O), (A,A), (O,A)\}$. The optimal retail price and profit under each sourcing strategy without and with blockchain adoption are summarized in Table 2.

We compare the optimal retail prices under different sourcing strategies with and without blockchain implementation in the following lemma.

Lemma 1. (1) Regardless of blockchain adoption, we have $p^i_{A,A} > p^i_{O,A} > p^i_{O,O}$, where $i \in \{N, B\}$. (2) Blockchain adoption increases the optimal retail price under each sourcing strategy, i.e., $p^B_j > p^N_j$, where

Table 2 Optimal retail price and profit under each strategy

	Sourcing strategy	Optimal retail price (p_j^i)	Retailer's optimal profit (Π_j^i)
Without blockchain (N)	(O, O)	$\frac{1}{2}$	$\frac{1}{4}(1-e_s\eta)-e_s\eta K$
	(A, A)	$\frac{1}{2}(1+\Delta)$	$\frac{1}{4}(1-\Delta)^2$
	(O, A)	$\frac{1}{2}\left(1+\frac{e_se_r\Delta}{1-e_s\eta(1-e_r)}\right)$	$\frac{[1-e_s\eta(1-e_r)-e_se_r\Delta]^2}{4[1-e_s\eta(1-e_r)]}-e_s\eta(1-e_r)K$
With blockchain (B)	(O, O)	$\frac{1}{2}(1+c_b)$	$\frac{1}{4}(1-c_b)^2(1-e_s\eta)-T_b$
	(A, A)	$\frac{1}{2}(1+c_b+\Delta)$	$\frac{1}{4}(1-c_b-\Delta)^2-T_b$
	(O, A)	$\frac{1}{2}(1+c_b+e_s\Delta)$	$\frac{1}{4}(1-c_b-e_s\Delta)^2-T_b$

$j \in \{(O, O), (A, A), (O, A)\}$.

Lemma 1 indicates that the contingent sourcing is safe but expensive. Then, the consumers have to pay more regardless of blockchain implementation. For concreteness, the optimal retail price increases in the degree of the retailer's dependence upon the alternative safe supplier. In addition, blockchain adoption incurs variable operations cost, which is also partially undertaken by consumers. Overall, consumers have to pay a premium price for health-safety, which is guaranteed by the safe supplier or blockchain adoption.

From Table 2, the retailer's expected profit drops to a nonpositive level under Strategy (O, O) or (O, A) in the absence of blockchain when the penalty cost of the infected product is sufficiently high, i.e., $\Pi_{O,O}^N \leqslant 0$, $K \geqslant \overline{K} = (1-e_s\eta)/4e_s\eta$ or $\Pi_{O,A}^N \leqslant 0$, $K \geqslant \overline{K}' = \frac{[1-e_s\eta(1-e_r)-e_se_r\Delta]^2}{4[1-e_s\eta(1-e_r)]e_s\eta(1-e_r)}$. However, the retailer's profit is guaranteed to be positive once he has incentive to adopt blockchain technology (i.e., $\Pi_j^B > 0$, $\forall j \in \{(O, O), (A, A), (O, A)\}$). We summarize the observation from Table 2 in the following remark.

Remark 1. The retailer faces the risk of ceasing business due to negative profit in the absence of blockchain when the penalty cost of the infected product is sufficiently high. Blockchain adoption enhances the retailer's continuous operations by guaranteeing profits, i.e., $\Pi_j^B > 0$, $\forall j \in \{(O, O), (A, A), (O, A)\}$.

Remark 1 implies that blockchain adoption helps improve supply chain resilience from the retailer's perspective by increasing profit and avoiding substantial penalty cost with efficient tracing and inspection.

4 Incentives for sourcing strategy and blockchain adoption

Focused on the supply chain resilience and tractable analysis, we consider a scenario where the retailer has to cease business due to a high penalty cost ($K > \overline{K}$) when sourcing from the original supplier only (i.e., Strategy (O, O)) in the absence of blockchain adoption. The results are robust and shown in the Supplementary Material by relaxing this assumption. We solve the problem backward by first solving the sourcing subgame equilibria without and with blockchain adoption. Then, the incentive for blockchain implementation is analyzed.

4.1 Optimal sourcing strategy without/with blockchain

In the absence of blockchain, the retailer faces the trade-off between a higher cost by sourcing from a safe supplier (Δ) and possible penalty cost by sourcing from a risky supplier (K). For identifying two crucial factors for sourcing strategy selection, we define two thresholds, namely, Δ_0 and K_0, where $\Delta_0 = 1-\frac{1-e_s\eta(1-e_r)-e_se_r}{\sqrt{1-e_s\eta(1-e_r)}-e_se_r}$, and $K_0 = \frac{1}{4e_s\eta(1-e_r)}\left[2(1-e_se_r)\Delta-\left(1-\frac{e_s^2e_r^2}{1-e_s\eta(1-e_r)}\right)\Delta^2\right]-\frac{1}{4} > \overline{K}$. The optimal sourcing strategy without blockchain adoption is shown in the following proposition.

Proposition 1. In the absence of blockchain adoption, the retailer adopts Strategy (O, A) if $\Delta \geqslant \Delta_0$ and $K \leqslant K_0$, but prefers Strategy (A, A) otherwise.

Proposition 1 indicates that it is more likely for the retailer to select Strategy (O, A) for health-safety concerns as the penalty cost K decreases or the extra emergency cost Δ increases. Without implementing blockchain, the retailer should always conduct the contingent sourcing (i.e., adopt Strategy (A, A)) when the extra emergency ordering cost is relatively low or the penalty cost for infection is sufficiently high. On the contrary, only when sourcing from the backup supplier is notably expensive while the penalty cost of the infected product detection is relatively low will the retailer be urged to make an ordering decision based on the updated belief of supplier's type after inspection. Note that the threshold Δ_0 increases in e_s and η, whereas threshold K_0 is affected by the two factors in an opposite manner. From Proposition

1, the retailer's preference over Strategy (O, A) is strengthened, as the proportion that the original supplier is risky and the product infected rate (e_s and η) decreases.

After adopting blockchain, the retailer's optimal sourcing strategy depends on the trade-off between high ordering cost from the safe backup (Δ) and variable cost of blockchain operations (c_b). Denote $\Delta_1=(1-c_b)\cdot(1-\sqrt{1-e_s\eta})/e_s$ as a threshold of the variable cost by sourcing from the safe supplier. We have Proposition 2.

Proposition 2. In the presence of blockchain adoption, the retailer's optimal sourcing strategy is (O, A) if $\Delta<\Delta_1$, but he prefers Strategy (O, O) otherwise.

In the presence of blockchain adoption, the retailer sticks to ordering from the original supplier when the extra emergency cost is sufficiently high (i.e., $\Delta\geqslant\Delta_1$), while making ordering decisions based on inspection otherwise. His incentive for relying on the original supplier is weakened by an increasing infected proportion (η), which leads to product recalls and returns without obtaining revenue. In addition, the retailer is more likely to order from the original supplier only in the presence of blockchain, as the variable operations cost of blockchain maintenance (c_b) increases. Proposition 2 also implies that Strategy (A, A) is substituted by the implementation of blockchain, which helps serve the market with safe food product by efficient tracing functions and accurate inspection. In addition, the efficient tracing ability also strengthens the retailer's incentive to adopt Strategy (O, O), which is excluded from the optimal strategies in the absence of blockchain adoption.

4.2 Incentive for blockchain adoption

On the basis of the retailer's sourcing strategy selection without/with blockchain adoption, we examine his incentive for blockchain adoption. Essentially, blockchain adoption is an outcome of the trade-off among its operations cost (c_b), extra emergency cost by sourcing from a backup supplier (Δ), and possible penalty cost due to infection detection (K)[1)]. The aforementioned factors are also inferred from Propositions 1 and 2. For notational purposes, we define thresholds K_1 and K_2 for the penalty cost K, where $K_1=\frac{1}{4e_s\eta(1-e_r)}\left[1-(1-c_b)^2+2(1-c_b-e_r)\cdot e_s\Delta-\left(1-\frac{e_r^2}{1-e_s\eta(1-e_r)}\right)e_s^2\Delta^2\right]-\frac{1}{4}$, and $K_2=\frac{1}{4e_s\eta(1-e_r)}\cdot\left[1-(1-c_b)^2(1-e_s\eta)-2e_se_r\Delta+\frac{e_s^2e_r^2}{1-e_s\eta(1-e_r)}\Delta^2\right]-\frac{1}{4}$. For the extra emergency cost (Δ), we also denote Δ_2 as another crucial threshold, where $\Delta_2=1-(1-c_b)\sqrt{1-e_s\eta}$. The retailer's incentive for blockchain adoption is summarized in the following proposition by changing the aforementioned costs.

Proposition 3. The retailer's incentive for blockchain adoption and corresponding sourcing strategy preferences are shown in Table 3.

Proposition 3 provides a clear picture about the retailer's incentive for blockchain adoption and corresponding preferences of sourcing strategy. Overall, blockchain adoption plays as a substitute for the alternative backup for supply chain resilience and maintenance through Strategy (O, O) when Δ and K are sufficiently high. At a low extra emergency cost Δ, the retailer prefers to adopt Strategy (O, A) with blockchain and source from the safe supplier only when infection is detected. From Table 3, the variable costs of blockchain operations and penalty costs from infection have a polarized effect on the retailer's incentive for blockchain implementation. As variable costs for blockchain operations increase from low to high, the retailer's incentive for implementing this technology is blunted. At low variable blockchain maintain costs (i.e., $0<c_b<\frac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s+(1-e_s)(1-\sqrt{1-e_s\eta})}$), the retailer adopts blockchain when the extra emergency cost Δ and infection penalty K are not low. When the variable cost c_b is relatively high (i.e., $c_b\geqslant\frac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s+(1-e_s)(1-\sqrt{1-e_s\eta})}$), only a sufficiently high marginal cost Δ and infection penalty K will trigger the implementation of blockchain. Undertaking high variable blockchain operations costs, the retailer chooses Strategy (O, O) only, where he benefits from the precise blockchain-based inspection and efficient tracking when infected risk is detected.

After checking the thresholds, we obtain two special cases. First, Strategy (O, O) is the only optimal strategy, and blockchain implementation is always preferred when the extra emergency cost is sufficiently high, i.e., $\Delta>\max\{\bar{\Delta},\Delta_i\}$, where $\bar{\Delta}=\frac{1}{e_se_r}\left[1-e_s\eta(1-e_r)-(1-c_b)\cdot\sqrt{[1-e_s\eta(1-e_r)](1-e_s\eta)}\right]$ and $i\in\{1,2\}$[2)]. It implies that blockchain implementation plays a role of complete substitution for contingent sourcing in advancing supply chain resilience, when the alternative backup supplier charges a high premium. On the contrary, the retailer has no incentive to adopt blockchain when the contingent sourcing is notably inexpensive (i.e., $\Delta<\min\{\Delta_0, c_b/(1-e_s)\}$). Under this condition, the

1) Although the fixed cost of the blockchain technology is substantial, it is viewed as a sunk cost and omitted in real operations afterward (Choi, 2020). In addition, its weakening effect on the retailer's incentive for blockchain adoption is intuitive. From these reasons, we neglect the fixed cost of blockchain implementation hereafter.

2) At low variable blockchain operations costs ($0<c_b<\frac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s+(1-e_s)(1-\sqrt{1-e_s\eta})}$), the condition for the optimal sourcing strategy is $\Delta>\max\{\bar{\Delta},\Delta_1\}$, while it becomes $\Delta>\max\{\bar{\Delta},\Delta_2\}$ at high variable costs, i.e., $c_b\geqslant\frac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s+(1-e_s)(1-\sqrt{1-e_s\eta})}$.

Table 3 Optimal decisions of blockchain adoption and sourcing strategy

Variable cost for blockchain operations (c_b)	Marginal cost of sourcing from a safe supplier (Δ)	Penalty cost for detected infection (K)	Blockchain adoption	Optimal sourcing strategy
$0<c_b<\frac{(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}{e_s+(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}$	$\Delta<\frac{c_b}{1-e_s}$	$K>K_0$	×	(A, A)
		$K\leqslant K_0$	×	(O, A)
	$\frac{c_b}{1-e_s}\leqslant\Delta<\Delta_1$	$K\leqslant K_1$	×	(O, A)
		$K>K_1$	√	(O, A)
	$\Delta_1\leqslant\Delta<1$	$K>K_2$	√	(O, O)
		$K\leqslant K_2$	×	(O, A)
$\frac{(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}{e_s+(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}\leqslant c_b<1$	$\Delta<\Delta_2$	$K\leqslant K_0$	×	(O, A)
		$K>K_0$	×	(A, A)
	$\Delta_2\leqslant\Delta<1$	$K\leqslant K_2$	×	(O, A)
		$K>K_2$	√	(O, O)

retailer always orders from the backup supplier with extra emergency costs (i.e., Strategy (A, A)).

5 All-win situation and government regulation

We explore the implications of sourcing strategies and blockchain adoption on the upstream of supplier and consumers in this section. From previous analysis, the retailer chooses Strategies (A, A) and (O, A) in the absence of blockchain, whereas the candidates become Strategies (O, O) and (O, A) after adopting the high technology. Accordingly, we focus on the four sourcing strategies hereafter.

The impacts of sourcing strategies and blockchain adoption on the original supplier's viability during the pandemic can be verified based on the model setting. From definition, the probabilities of the supplier's continuous operations under various strategies with and without implementing blockchain can be shown in the following remark.

Remark 2. $\beta_{A,A}^N<\beta_{O,A}^B<\beta_{O,A}^N<\beta_{O,O}^B=1$.

Under Strategy (O, A), blockchain adoption reduces the probability of the supplier's continuous operations (i.e., $\beta_{O,A}^B<\beta_{O,A}^N$), as the high technology helps the retailer improve inspection accuracy. Implementing blockchain helps the supplier raise continuous operations probability to 1 under Strategy (O, O). The main reason behind the result is that blockchain enables efficient tracing once the infection is reported, and the retailer can depend on the original supplier as the health-safety concerns are reduced. From Table 3, the situation preferred by the original supplier is achieved when the infection penalty K is sufficiently high. Recall that blockchain adoption eliminates the interruption risk faced by the retailer from Remark 1. Then, implementing blockchain further benefits the supply chain by achieving resilience under Strategy (O, O).

Next, we investigate the value of blockchain adoption with sourcing strategies from the consumers' perspective. We derive the consumer surplus CS_j^i as follows:

$$CS_j^i=\int_{p_j^i}^1(v-p)f(v)\,\mathrm{d}v, \tag{7}$$

where p_j^i is the optimal retail price under Strategy j, $i\in\{N, B\}$ and $j\in\{(O, O), (A, A), (O, A)\}$. After substituting the optimal retail price into the consumer surplus under each sourcing strategy without/with blockchain adoption, we have Table 4.

On the basis of Table 4, we compare the consumer surplus under each scenario and have Proposition 4.

Proposition 4. The consumers are benefited by the implementation of blockchain with Strategy (O, O) (i.e., $CS_{O,O}^B>\max\{CS_{O,A}^B, CS_{O,A}^N, CS_{A,A}^N\}$) if and only if the additional ordering cost is comparatively higher than the variable cost of blockchain maintenance (i.e., $\Delta\geqslant\Delta_{CS}$, where $\Delta_{CS}=[1-e_s\eta(1-e_r)]c_b/e_se_r$); otherwise, they prefer Strategy (O, A) without blockchain adoption (i.e., $CS_{O,A}^N>\max\{CS_{A,A}^N, CS_{O,O}^B, CS_{O,A}^B\}$).

Proposition 4 implies important insights from the consumers' perspective by showing the results on how the sourcing strategy and blockchain adoption affect the consumer surplus. When the additional ordering cost is sufficiently large, the consumers prefer the retailer to adopt Strategy (O, O) and blockchain technology at the same time. When the extra emergency cost drops below the threshold (i.e., $\Delta<\Delta_{CS}$), consumers prefer the retailer

Table 4 Consumer surplus under sourcing strategies without/with blockchain

	Sourcing strategy	Consumer surplus
Without blockchain (N)	(A, A)	$\frac{1}{8}(1-\Delta)^2$
	(O, A)	$\frac{1}{8}\left(1-\frac{e_se_r\Delta}{1-e_s\eta(1-e_r)}\right)^2$
With blockchain (B)	(O, O)	$\frac{1}{8}(1-c_b)^2$
	(O, A)	$\frac{1}{8}(1-c_b-e_s\Delta)^2$

to forgo implementing the high technology and receive benefits from Strategy (O, A). From Table 4, $CS^B_{O,O} > CS^B_{O,A}$ always holds, whereas $CS^N_{A,A}$ decreases in Δ. Accordingly, the relationship of consumer surplus under the three strategies depends on the extra emergency cost and variable cost of blockchain operations only. Specifically, $CS^N_{A,A} > CS^B_{O,O} > CS^B_{O,A}$, if $\Delta \leqslant c_b$; $CS^B_{O,O} > CS^N_{A,A} > CS^B_{O,A}$, if $c_b < \Delta \leqslant c_b/(1-e_s)$; and $CS^B_{O,O} > CS^B_{O,A} > CS^N_{A,A}$, if $\Delta > c_b/(1-e_s)$. Proposition 4 also implies that the consumer surplus decreases as the retailer increasingly depends on the contingent sourcing without/with blockchain adoption (i.e., $CS^B_{O,O} > CS^B_{O,A}$ and $CS^N_{O,A} > CS^N_{A,A}$), as they have to undertake a part of substantial extra emergency costs.

From Remark 2 and Propositions 3 and 4, an all-win situation can be achieved for the supplier, retailer and consumers when the retailer chooses Strategy (O, O) and adopts blockchain technology. Focused on the conditions that trigger the retailer's corresponding strategic decision which leads to an all-win situation, we propose that the government should consider providing subsidy and setting regulation to help. It has been reported that governments in Australia, China, and Germany support the development of blockchain technology and supply chain resilience with funding boosts, especially during the pandemic (Choi and Shi, 2022b). To help suppliers get through the epidemic, the government offers subsidy s per unit to the retailer if he orders from the original one[1]. For the setting of regulation, the government can charge an additional penalty b to the retailer once the infected product is detected in the market. We have Proposition 5.

Proposition 5. To achieve an all-win situation by urging the retailer to adopt blockchain and Strategy (O, O), the government can set the additional penalty as $b \geqslant \bar{b}$ and provide the subsidy $s \geqslant \bar{s}$, where $\bar{b} = (K_2 - K)^+$, $\bar{s} = (\max\{\Delta_1, \Delta_{CS}\} - \Delta)^+$ at a low variable cost of blockchain operations ($c_b < \dfrac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s + (1-e_s)(1-\sqrt{1-e_s\eta})}$), and $\bar{s} = (\max\{\Delta_2, \Delta_{CS}\} - \Delta)^+$ at a high variable cost of blockchain operations ($c_b \geqslant \dfrac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s + (1-e_s)(1-\sqrt{1-e_s\eta})}$).

Proposition 5 indicates a case in which the government plays a coordinating role in helping the supply chain achieve an all-win situation for the supplier, retailer, and consumers, who are all guaranteed to be benefited by the implementation of blockchain under Strategy (O, O). At the same time, supply chain resilience can be realized, as the original supplier no longer faces the risk of losing transactions (i.e., $\beta^B_{O,O} = 1$). Moreover, the government's strategic response is a carrot and stick policy to the retailer. On the one hand, the subsidy provided by the government is devoted to making it more economical to purchase from the original supplier compared with the contingent sourcing. On the other hand, an additional penalty is charged to urge the retailer to adopt blockchain for health-safety concerns.

6 Further analysis

There are two types of consumers in the market. A group of consumers are not affected by information about the risk of food infection. They are either uninformed about the implied sourcing risk or aleatory about products with potential risk. Then, the utility of these consumers remains the same as that in the basic model, i.e., $u = v - p$. The remaining consumers have serious worries about being infected. Hence, they have significant preference for blockchain-based features, such as tracing, reliable information, and efficient inspection, which reduce their health-safety concerns. Specifically, they behave like the normal consumers with utility $u = v - p$ without blockchain adoption. Therefore, the consumers' preference for blockchain does not affect results in the absence of this high technology. As the consumers' health-safety concerns are significantly reduced by the implementation of blockchain, their utility increases with blockchain adoption as a result, i.e., $u = v - p + \theta$, where $\theta \in (0, 1)$ (Yang et al., 2021; Choi and Shi, 2022b). We assume that the market size is equal for the two types of consumers, which is robust to the main results in this work. The retailer's expected profits under Strategies (O, O), (A, A), and (O, A) in the presence of blockchain are as follows:

$$\tilde{\pi}^{R,B}_{O,O} = (p - c_b)\left[(1-e_s)\left(1 - p + \frac{\theta}{2}\right) + e_s\left(1 - p + \frac{\theta}{2}\right)(1-\eta)\right] - T_b, \tag{8}$$

$$\tilde{\pi}^{R,B}_{A,A} = (p - c_b - \Delta)\left(1 - p + \frac{\theta}{2}\right) - T_b, \tag{9}$$

$$\tilde{\pi}^{R,B}_{O,A} = e_s(p - c_b - \Delta)\left(1 - p + \frac{\theta}{2}\right) + (1-e_s)(p - c_b)\left(1 - p + \frac{\theta}{2}\right) - T_b. \tag{10}$$

Similar to the previous analysis, it can be shown that the profit is concave in retail price under each sourcing strategy in the presence of blockchain adoption with consideration of consumers' health-safety concerns. We use subscript j to represent the sourcing strategies, where $j \in \{(O, O), (A, A), (O, A)\}$. The optimal retail price ($\tilde{p}^B_j$) and profit ($\tilde{\Pi}^B_j$) under each sourcing strategy with blockchain adoption are summarized in Table 5. On the

[1] It is equivalent to the scenario where the government offers subsidy to the original supplier directly.

Table 5 Optimal retail price and profit under each strategy with blockchain adoption considering consumers' preferences

Sourcing strategy	Optimal retail price ($\tilde{p}_j^B$)	Retailer's optimal profit ($\tilde{\Pi}_j^B$)
(O, O)	$\frac{1}{2}\left(1+\frac{\theta}{2}+c_b\right)$	$\frac{1}{4}\left(1+\frac{\theta}{2}-c_b\right)^2(1-e_s\eta)-T_b$
(A, A)	$\frac{1}{2}\left(1+\frac{\theta}{2}+c_b+\Delta\right)$	$\frac{1}{4}\left(1+\frac{\theta}{2}-c_b-\Delta\right)^2-T_b$
(O, A)	$\frac{1}{2}\left(1+\frac{\theta}{2}+c_b+e_s\Delta\right)$	$\frac{1}{4}\left(1+\frac{\theta}{2}-c_b-e_s\Delta\right)^2-T_b$

basis of the results in Table 5, we compare the optimal retail prices under different sourcing strategies after considering consumers' preferences for blockchain in Lemma 2.

Lemma 2. (1) In the presence of blockchain adoption and consumers' preference for this high technology, the optimal price increases in retailer's dependence on contingent sourcing $\tilde{p}_{A,A}^B > \tilde{p}_{O,A}^B > \tilde{p}_{O,O}^B$. (2) Consumers' preference over blockchain adoption amplifies the gap of retail prices under each sourcing strategy caused by the high technology, i.e., $\tilde{p}_j^B > p_j^B > p_j^N$, where $j \in \{(O, O), (A, A), (O, A)\}$.

Lemma 2 further illustrates that consumers have to undertake a part of costs incurred to the retailer who utilizes contingent sourcing or high-tech implementation to serve safe food products.

Next, we examine the retailer's optimal sourcing strategy and incentive for blockchain adoption, considering consumers' high-tech preference. We define the thresholds $\tilde{K}_1$ and $\tilde{K}_2$ for the penalty cost K, where $\tilde{K}_1 = \frac{1}{4e_s\eta(1-e_r)} \cdot\left[1-\left(1+\frac{\theta}{2}-c_b\right)^2+2\left(1+\frac{\theta}{2}-c_b-e_r\right)e_s\Delta-\left(1-\frac{e_r^2}{1-e_s\eta(1-e_r)}\right)e_s^2\Delta^2\right] -\frac{1}{4}$, and $\tilde{K}_2 = \frac{1}{4e_s\eta(1-e_r)}\left[1-\left(1+\frac{\theta}{2}-c_b\right)^2(1-e_s\eta) -2e_se_r\Delta+\frac{e_s^2e_r^2}{1-e_s\eta(1-e_r)}\Delta^2\right]-\frac{1}{4}$. In addition, we use $\tilde{\Delta}_1$ and $\tilde{\Delta}_2$ to represent the two crucial thresholds for the extra emergency cost (Δ), where $\tilde{\Delta}_1 = (1+\theta/2-c_b)\cdot(1-\sqrt{1-e_s\eta})/e_s$, and $\tilde{\Delta}_2 = 1-(1+\theta/2-c_b)\sqrt{1-e_s\eta}$. The retailer's incentive for blockchain adoption and optimal sourcing strategies are summarized in the following proposition.

Proposition 6. The retailer's incentive for blockchain adoption and corresponding sourcing strategy preferences are given in Table 6.

On the basis of Propositions 3 and 6, the retailer's incentive for blockchain adoption is strengthened by the consumers' preference for this high technology. First, when the variable cost of blockchain operations is sufficiently low (i.e., $0 < c_b < \theta/2$), the retailer is more likely to adopt blockchain, which is preferred by some consumers. Second, the thresholds of penalty cost are reduced by the consumers' preference (i.e., $K_1 > \tilde{K}_1$ and $K_2 > \tilde{K}_2$), which strengthens the retailer's motivation to adopt blockchain for food health-safety concerns.

From Lemma 2, both types of consumers undertake a higher retail price after considering consumers' preference for blockchain adoption. Next, we check the consumer surplus in the blockchain implementation with consumers' preference. From the definition, the consumer surpluses with blockchain and consumers' preference under Strategies (O, O) and (O, A) are $\widetilde{CS}_{O,O}^B = (1+\theta/2-c_b)^2/8+\theta^2/8$ and $\widetilde{CS}_{O,A}^B = (1+\theta/2-c_b-e_s\Delta)^2/8+\theta^2/8$, respectively. We compare the consumer surplus under each scenario and have Proposition 7.

Proposition 7. (1) In the presence of blockchain adoption, consumers' preference for this high technology increases the consumer surplus under each sourcing strategy (i.e., $\widetilde{CS}_{O,O}^B > CS_{O,O}^B$ and $\widetilde{CS}_{O,A}^B > CS_{O,A}^B$). (2) With the consideration of consumers' preference, the consumer surplus is the highest with the implementation of blockchain under Strategy (O, O) (i.e., $\widetilde{CS}_{O,O}^B > \max\{\widetilde{CS}_{O,A}^B, CS_{O,A}^N, CS_{A,A}^N\}$) if and only if the additional ordering cost is comparatively higher than the variable cost of blockchain maintenance (i.e., $\Delta \geqslant \tilde{\Delta}_{CS}$, where $\tilde{\Delta}_{CS} = \left[1-\sqrt{(1+\theta/2-c_b)^2+\theta^2}\right]\left[1-e_s\eta(1-e_r)\right]/e_se_r$); otherwise, consumers prefer Strategy (O, A) without blockchain adoption (i.e., $CS_{O,A}^N > \max\{\widetilde{CS}_{O,O}^B, \widetilde{CS}_{O,A}^B, CS_{A,A}^N\}$).

Interestingly, the consumer surplus increases when some consumers with health-safety concerns have preference for blockchain adoption, although both types of consumers have to pay a higher retail price. Note that $\Delta \geqslant \tilde{\Delta}_{CS}$ always holds when the consumers' preference for blockchain is significantly strong (i.e., $\sqrt{(1+\theta/2-c_b)^2+\theta^2} \geqslant 1$). Under this condition, the consumer surplus is always highest with blockchain adoption under Strategy (O, O).

From Propositions 6 and 7, consumers' health-safety concern and preference for blockchain implementation strengthen the retailer's incentive to adopt the high technology and increase the consumers' benefit under Strategy (O, O) at the same time. In addition, consumers' preference has no influence on the supplier's continuous operations (β_j^i) from the definition. Then, we investigate an all-win situation under the extended model.

Similar to the previous analysis, an all-win situation can be achieved when the retailer chooses Strategy (O, O) and adopts blockchain technology. We have Proposition 8.

Proposition 8. To achieve an all-win situation by urging the retailer to adopt blockchain and Strategy (O, O), the government can set the additional penalty as $b \geqslant \tilde{b}$ and provide subsidy $s \geqslant \tilde{s}$, where $\tilde{b} = (\tilde{K}_2 - K)^+ < \bar{b}$, $\tilde{s} = (\max\{\tilde{\Delta}_1, \tilde{\Delta}_{CS}\}-\Delta)^+$ at a low variable cost for blockchain implementation ($c_b < \frac{\theta}{2}+\frac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s+(1-e_s)(1-\sqrt{1-e_s\eta})}$),

Table 6 Optimal sourcing strategy and incentive for blockchain adoption with consumers' preference

Variable cost for blockchain operations (c_b)	Marginal cost of sourcing from a safe supplier (Δ)	Penalty cost for detected infection (K)	Blockchain adoption	Optimal sourcing strategy
$0 < c_b < \frac{\theta}{2}$	$0 < \Delta < \tilde{\Delta}_1$	$K \leqslant \tilde{K}_1$	×	(O, A)
		$K > \tilde{K}_1$	√	(O, A)
	$\tilde{\Delta}_1 \leqslant \Delta < 1$	$K > \tilde{K}_2$	√	(O, O)
		$K \leqslant \tilde{K}_2$	×	(O, A)
$\frac{\theta}{2} \leqslant c_b < \frac{\theta}{2} + \frac{(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}{e_s+(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}$	$\Delta < \frac{c_b-\theta/2}{1-e_s}$	$K > K_0$	×	(A, A)
		$K \leqslant K_0$	×	(O, A)
	$\frac{c_b-\theta/2}{1-e_s} \leqslant \Delta < \tilde{\Delta}_1$	$K \leqslant \tilde{K}_1$	×	(O, A)
		$K > \tilde{K}_1$	√	(O, A)
	$\tilde{\Delta}_1 \leqslant \Delta < 1$	$K > \tilde{K}_2$	√	(O, O)
		$K \leqslant \tilde{K}_2$	×	(O, A)
$\frac{\theta}{2} + \frac{(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)}{e_s+(1-e_s)\left(1-\sqrt{1-e_s\eta}\right)} \leqslant c_b < 1$	$\Delta < \tilde{\Delta}_2$	$K \leqslant K_0$	×	(O, A)
		$K > K_0$	×	(A, A)
	$\tilde{\Delta}_2 \leqslant \Delta < 1$	$K \leqslant \tilde{K}_2$	×	(O, A)
		$K > \tilde{K}_2$	√	(O, O)

and $\tilde{s} = (\max\{\tilde{\Delta}_2, \tilde{\Delta}_{CS}\} - \Delta)^+ < \bar{s}$ at a high variable cost for blockchain implementation ($c_b \geqslant \frac{\theta}{2} + \frac{(1-e_s)(1-\sqrt{1-e_s\eta})}{e_s+(1-e_s)(1-\sqrt{1-e_s\eta})}$).

Proposition 8 indicates that the government can help the food supply chain achieve an all-win situation by charging a smaller amount of additional penalty and subsidizing less in most cases. Only when the variable cost for blockchain operations is sufficiently low and $\tilde{\Delta}_1 > \tilde{\Delta}_{CS}$ can the government offer a larger amount of subsidy to drive the retailer to choose Strategy (O, O), as conducting contingent sourcing with blockchain adoption is efficient for the retailer. As the value of blockchain adoption amplifies for the retailer and consumers when some of them have health-safety concerns with blockchain preference, it is easier for the government to coordinate the food supply chain with additional penalty for infection and subsidy for original sourcing.

7 Conclusions

Food supply chains now have to face challenges due to the COVID-19 outbreak. Food infection, once detected by the market or regulators, often leads to dramatic losses to the retailers and suppliers. It has been shown different sourcing strategies based on inspection, especially the contingent sourcing from a backup safe food supplier, are efficient to combat the health-safety concerns in the market. However, as the inspection is not precise and contingent sourcing incurs substantial extra emergency costs, it is not always optimal or efficient in practice. In addition, from the perspective of supply chain resilience, the original supplier suffers from the retailer's contingent sourcing during the pandemic, as she may fail to match other retailers in the market or stay in business. In addition, blockchain-based features, such as efficient traceability and reliable information, help solve issues in food supply chains under the epidemic. In view of the trade-off among blockchain operations cost, emergency cost for contingent sourcing, and the possible penalty cost due to infection, we investigate the retailer's incentive for blockchain adoption and optimal sourcing strategy. On the basis of the analytical model that evaluates blockchain adoption and contingent sourcing strategy in food supply chains, we have derived the optimal retail prices and sourcing strategies with and without blockchain implementation. After comparing the related performances from the perspectives of the retailer, the original supplier, and consumers, we identify conditions for an all-win situation enabled by blockchain adoption.

As a concluding remark, we highlight the results obtained in our work to echo our research questions raised before. We have shown that blockchain adoption is an outcome of the trade-off among its operations cost, extra emergency cost, and possible penalty cost due to infection detection. Specifically, blockchain becomes a substitute for the backup supplier in achieving supply chain resilience when the retailer sticks to sourcing from the original supplier at sufficiently high infection penalty and emergency ordering costs. Moreover, an all-win situation can be achieved for the supplier, retailer, and consumers when the retailer sources from the original supplier and adopts blockchain technology. Focused on the conditions that trigger the retailer's corresponding strategic decision, which leads to an all-win situation, we suggest that the government should adopt a carrot and stick policy to the retailer to help achieve supply chain coordination. Specifically, governments are urged to provide subsidy to make it more economical to purchase from the original supplier compared with the contingent sourcing and charge an additional penalty to drive the retailer to reduce health-safety concerns with blockchain. Finally, we have further studied models considering consumers' preference for blockchain technologies.

In this paper, we consider the scenario where a food retailer orders from a supplier with potential risk and utilizes contingent sourcing and inspection to reduce infection risk. It will be interesting to further extend the model setting with dual sourcing. In addition, how blockchain can play a role in food industries is another promising research direction. For example, adopting blockchain may hurt the suppliers' privacy. Then, whether the suppliers still have incentives to link information to blockchain remains unknown. In the current study, we propose that the blockchain adoption may achieve an all-win situation from the perspectives of the retailer, supplier, supply chain resilience, and consumers under certain conditions or with the government's coordination. In the future, the government's regulation deserves more exploration. Therefore, it is of great interest to study how governments should set the penalty cost for food infection under COVID-19 and offer subsidy for certain sourcing strategy to improve supply chain resilience and social welfare.

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://dx.doi.org/10.1007/s42524-022-0232-2 and is accessible for authorized users.

References

Babich V, Tang C (2012). Managing opportunistic supplier product adulteration: Deferred payments, inspection, and combined mechanisms. Manufacturing & Service Operations Management, 14(2): 301–314

Blackmon L, Chan R, Carbral O, Chintapally G, Dhara S, Felix P, Jagdish A, Konakalla S, Labana J, McIlvain J, Stone J, Tang C S, Torres J, Wu W (2021). Rapid development of a decision support system to alleviate food insecurity at the Los Angeles Regional Food Bank amid the COVID-19 pandemic. Production and Operations Management, 30(10): 3391–3407

Casino F, Kanakaris V, Dasaklis T K, Moschuris S, Stachtiaris S, Pagoni M, Rachaniotis N P (2021). Blockchain-based food supply chain traceability: A case study in the dairy sector. International Journal of Production Research, 59(19): 5758–5770

Chen C, Zhang J, Delaurentis T (2014). Quality control in food supply chain management: An analytical model and case study of the adulterated milk incident in China. International Journal of Production Economics, 152: 188–199

Chen Q, Jiang X, Zhang Y (2019). The effects of audit quality disclosure on audit effort and investment efficiency. Accounting Review, 94(4): 189–214

Choi T M (2020). Innovative "bring-service-near-your-home" operations under coronavirus (COVID-19/SARS-CoV-2) outbreak: Can logistics become the messiah? Transportation Research Part E: Logistics and Transportation Review, 140: 101961

Choi T M, Shi X (2022a). Reducing supply risks by supply guarantee deposit payments in the fashion industry in the "new normal after COVID-19". Omega, 109: 102605

Choi T M, Shi X (2022b). On-demand ride-hailing service platforms with hired drivers during coronavirus (COVID-19) outbreak: Can blockchain help? IEEE Transactions on Engineering Management, in press, doi:10.1109/TEM.2021.3131044

Choi T M, Wen X, Sun X, Chung S H (2019). The mean-variance approach for global supply chain risk analysis with air logistics in the blockchain technology era. Transportation Research Part E: Logistics and Transportation Review, 127: 178–191

Dong L, Jiang P, Xu F (2022). Impact of traceability technology adoption in food supply chain networks. Management Science, in press, doi:10.1287/mnsc.2022.4440

El Baz J, Ruel S (2021). Can supply chain risk management practices mitigate the disruption impacts on supply chains' resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. International Journal of Production Economics, 233: 107972

Felix I, Martin A, Mehta V, Mueller C (2020). US food supply chain: Disruptions and implications from COVID-19. Online Report from McKinsey

Felix I, Mazuera C, Salguero J, Sänger F (2022). Risk and resilience in consumer-goods supply chains. Online Report from McKinsey

Fernandez M (2021). Blockchain-enabled digital health credentials to help businesses reopen safely and build the future of digital ecosystems. Visual White Paper from Frost & Sullivan

Firouz M, Keskin B, Melouk S (2017). An integrated supplier selection and inventory problem with multi-sourcing and lateral transshipments. Omega, 70: 77–93

He L, Rong Y, Shen Z M (2020). Product sourcing and distribution strategies under supply disruption and recall risks. Production and Operations Management, 29(1): 9–23

Hosseini S, Ivanov D, Dolgui A (2019). Review of quantitative methods for supply chain resilience analysis. Transportation Research Part E: Logistics and Transportation Review, 125: 285–307

Hu B, Kostamis D (2015). Managing supply disruptions when sourcing from reliable and unreliable suppliers. Production and Operations Management, 24(5): 808–820

Ivanov D, Dolgui A (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability, a position paper motivated by COVID-19 outbreak. International Journal of Production Research, 58(10): 2904–2915

Jin C, Levi R, Liang Q, Renegar N, Springs S, Zhou J, Zhou W (2021). Testing at the source: Analytics-enabled risk-based sampling of food supply chains in China. Management Science, 67(5): 2985–2996

Li K, Lee J Y, Gharehgozli A (2021). Blockchain in food supply chains: A literature review and synthesis analysis of platforms, benefits and challenges. International Journal of Production Research, in press, doi:10.1080/00207543.2021.1970849

Liu S, Hua G, Kang Y, Edwin Cheng T C, Xu Y (2022). What value does blockchain bring to the imported fresh food supply chain?

Transportation Research Part E: Logistics and Transportation Review, 165: 102859

McKinsey (2020). A shift to digital: How COVID-19 has changed selling models. Online Report

Piramuthu S, Farahani P, Grunow M (2013). RFID-generated traceability for contaminated product recall in perishable food supply networks. European Journal of Operational Research, 225(2): 253–262

Plambeck E L, Taylor T A (2016). Supplier evasion of a buyer's audit: Implications for motivating supplier social and environmental responsibility. Manufacturing & Service Operations Management, 18(2): 184–197

Ponomarov S Y, Holcomb M C (2009). Understanding the concept of supply chain resilience. International Journal of Logistics Management, 20(1): 124–143

PwC (2020). Time for trust: How blockchain will transform business and the economy. Online Report

Rogerson M, Parry G C (2020). Blockchain: Case studies in food supply chain visibility. Supply Chain Management, 25(5): 601–614

Roth A V, Tsay A A, Pullman M E, Gray J V (2008). Unraveling the food supply chain: Strategic insights from China and the 2007 recalls. Journal of Supply Chain Management, 44(1): 22–39

Sharma A, Adhikary A, Borah S B (2020). COVID-19's impact on supply chain decisions: Strategic insights from NASDAQ 100 firms using Twitter data. Journal of Business Research, 117: 443–449

Shi X, Yao S, Luo S (2021). Innovative platform operations with the use of technologies in the blockchain era. International Journal of Production Research, in press, doi:10.1080/00207543.2021.1953182

Singh S, Kumar R, Panchal R, Tiwari M K (2021). Impact of COVID-19 on logistics systems and disruptions in food supply chain. International Journal of Production Research, 59(7): 1993–2008

Tao Y, Lai X, Zhou S (2020). Information sharing in a transparent supply chain with transportation disruptions and supplier competition. Annals of Operations Research, in press, doi:10.1007/s10479-020-03724-3

Vu N, Ghadge A, Bourlakis M (2021). Blockchain adoption in food supply chains: A review and implementation framework. Production Planning and Control, in press, doi:10.1080/09537287.2021.1939902

Wang Y, Yu Y (2020). Flexible strategies under supply disruption: The interplay between contingent sourcing and responsive pricing. International Journal of Production Research, 58(16): 4829–4850

Wu X Y, Fan Z P, Cao B B (2021). An analysis of strategies for adopting blockchain technology in the fresh product supply chain. International Journal of Production Research, in press, doi:10.1080/00207543.2021.1894497

Yang L, Zhang J, Shi X (2021). Can blockchain help food supply chains with platform operations during the COVID-19 outbreak? Electronic Commerce Research and Applications, 49: 101093

Yao S, Zhu K (2020). Combating product label misconduct: The role of traceability and market inspection. European Journal of Operational Research, 282(2): 559–568

Zhao G, Liu S, Lopez C, Lu H, Elgueta S, Chen H, Boshkoska B M (2019). Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions. Computers in Industry, 109: 83–99