Green Agri-Food Blockchain Technology for Investment Decision-Making under Cost Information Constraints

Ren Gao, Shengqiang Huang, Baolin Li

***Abstract*—Addressing the potential for cost misreporting in the green agri-food supply chain (GAFSC) within the context of cost information constraints, this study formulates a Stackelberg game model where the retailer takes the lead, followed by the manufacturer and logistics provider. A comprehensive analysis investigates the impact of cost misreporting on decision-making among members and profit distribution. Additionally, the study explores the use of blockchain technology for transparent cost information management and identifies the investment thresholds for various members, essential in their decision-making. The research findings show that, to maximize benefits, manufacturers and logistics providers within the GAFSC tend to engage in controlled cost misreporting to compensate for decision-making disadvantages and enhance profitability. However, the dissemination of false cost information leads to profit loss within the GAFSC and a reduction in operational efficiency. The retailer's decision to adopt blockchain technology depends on the associated investment cost. When this cost falls below a critical threshold, implementing this technology enhances the profits of the retailer, logistics provider, and the entire supply chain, whereas increasing technology investment costs lead to declining profits for each member. Finally, the study offers specific analyses that further validate these findings.**

***Index Terms*—Cost information constraints, green agri-food, misreporting behavior, blockchain technology, game theory**

I. Introduction

THE No.1 Central Document of China for 2022 marked a historic moment by incorporating green agricultural and rural development within the framework of industrial revitalization and rural progress. This shift represents a departure from mere pollution control towards the pursuit of sustainable industrial growth in China's agricultural and rural sectors. The imperative now revolves around cultivating green industries, delivering high-quality and affordable agri-food products, and ensuring the consistent provision of green, high-quality agri-foods. These steps hold the key to augmenting farmers' incomes and fostering agricultural advancement through sustainable transformation [1], [2]. Simultaneously, China's economic trajectory is transitioning from rapid growth to high-quality development. As consumer affluence grows and environmental consciousness, as well as concerns about food safety, heighten, there's an evident inclination towards purchasing green agri-foods [3]. Nonetheless, in contrast to conventional agri-foods, green agri-foods encounter significant hurdles in consumer acceptance and market penetration, attributable to factors like elevated pricing, product adulteration, and information barriers. On the one hand, consumers grapple with discerning the fundamental distinctions between green and conventional agri-foods, based solely on their appearance and short-term nutritional effects [4]. Meanwhile, the higher production costs linked to green agri-foods result in elevated price tags compared to their conventional counterparts, thus contributing to a "fuzzy effect" that hinders cost-effectiveness in consumer psychology [5]. The intricate cost structures and high input expenses may prompt members of the GAFSC to conceal their cost structures for profit maximization. However, this practice raises communication costs among members, negatively impacting agri-food pricing and impeding efficient supply chain operations. Notably, retailers hold significant decision-making authority in agri-food trade. In contrast to conventional agri-foods, where costs and profits are relatively transparent, green agri-foods command higher prices, yet the specifics of their production and transportation expenses remain opaque. This disparity offers both motivation and opportunities for manufacturers and logistics providers to misrepresent costs to retailers, primarily to safeguard their own interests. While manipulating the reporting of production and transportation costs to raise prices and boost profits is common, such practices can result in unwarranted losses for retailers and adversely affect the GAFSC.

To evaluate the potential consequences of cost misreporting by manufacturers and logistics providers within the GAFSC on decision-making, this study suggests that retailers utilize blockchain technology to monitor cost information associated with green agri-foods. This approach can alleviate profit losses resulting from inaccurate reporting by other members. Employing Stackelberg game theory, this paper examines the impact of blockchain technology on cost management within the GAFSC. It accomplishes this by

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computing the critical investment threshold for this technology and analyzing the shifts in decision-making and profitability before and after its implementation. The primary objective of this paper is to serve as a point of reference for maintaining the stability of supply chain operations, expediting the assimilation of emerging technologies and green sectors, and continually advancing the sustainable development of agriculture and rural regions.

II. Literature Review

Information sharing is crucial for members of the agri-food supply chain (AFSC) and the entire supply chain system. For instance, manufacturers, positioned upstream, remain distanced from consumers and must depend on other stakeholders to acquire market demand information. Meanwhile, retailers, positioned downstream, necessitate data on both agri-food costs and quality [6]. Notably, a scarcity of information exchange between these upstream and downstream entities is a recurrent issue in practical scenarios, resulting in pervasive information asymmetry that can potentially lead to supply chain inefficiencies [7]. Yu *et al.* [8] explore the impact of government-provided agri-food market information and recommendations on decision-making within the system. Using a two-stage game model, they demonstrate that such an approach can effectively align the interests of all AFSC members. Further, Luo *et al.* [9] identify information asymmetry as a significant contributor to agri-food quality issues, and propose a new approach using fuzzy big data and large-scale group decision-making (LSGDM) for robust theoretical data in AFSC research. Godar *et al.* [10] delve into the impact of information transparency on profit distribution among supply chain members and the overall enhancement of supply chain sustainability. They advocate for reinforcing information governance and adopting an improved accountability system within the supply chain. Considering the impact of misreported cost information on the AFSC, Yan *et al.* [11] examine it from the producers' standpoint, Song *et al.* [12] and Yu *et al.* [13] approach it from the retailers' standpoint, while Feng *et al.* [14] offer an analysis from the logistics providers' standpoint. These studies collectively demonstrate that supply chain members tend to inflate costs to hike product prices, augmenting their own profits while diminishing others', resulting in market instability and AFSC vulnerability. Therefore, managing information transparency effectively is vital for instilling consumer confidence and fostering motivation in the green agri-food market. Information constraints pose a significant challenge to the sustainable development of the GAFSC, which currently relies on economic and technical measures to promote information sharing among its members.

Economic measures in the supply chain mainly center on forging alliances through contractual agreements among participants to incentivize information sharing. Guo *et al.* [15] introduce a flexible ordering strategy grounded in revenue-sharing and penalty-feedback contracts, enhancing agricultural logistics information exchange and data resource sharing while elevating overall income levels throughout the supply chain. Li *et al.* [16] investigate information asymmetry in the direct selling process of agri-foods, analyzing the impact of logistics costs and information sharing levels on supply chain members' profits. They develop a profit-sharing contract rooted in principal-agent theory and contract theory to enhance supply chain operational efficiency. Ma *et al.* [17] examine the impact of asymmetric demand information on order quantity and retail pricing in a three-echelon GAFSC. They propose a coordination contract based on cost and revenue sharing for the transaction process in the supply chain, aiming for Pareto improvement in all members' incomes. Gao *et al.* [18] explore the use of three incentive contracts: cost-sharing, revenue-sharing, and revenue-and-cost-sharing, to facilitate information exchange in the supply chain. In certain scenarios, Li *et al.* [19] suggest that implementing price discounts and revenue-sharing contracts can incentivize manufacturers and retailers to adopt blockchain technology for information sharing, thus achieving coordination within the AFSC. It's important to note that despite contract coordination's commonality in promoting information sharing among supply chain members, there remains a risk of default due to some members' noncompliance with the agreement.

The emergence of blockchain technology has ushered in opportunities for supply chain transparency and traceability [20]. Simultaneously, the academic community actively investigates its integration within the agri-food industry. Yang *et al.* [21] leverage the decentralized, tamper-proof, and traceable nature of blockchain technology to create an information query system for AFSC, boosting the transparency and credibility of agri-food information. Kamble *et al.* [22], Bai *et al.* [23], and Nayal *et al.* [24] underscore the potential of emerging technologies, such as blockchain, in optimizing AFSC, creating a data-driven sustainable digital supply chain environment that mitigates disruptions stemming from trust issues. Wang *et al.* [25] propose a trust framework rooted in smart contracts, which holds significant value in ensuring agri-food quality, safety, and traceability. Hu *et al.* [26] develop a blockchain-based trust framework for the GAFSC, aiming to reduce operational costs and enhance efficiency. Feng *et al.* [27] propose a blockchain-based agricultural food traceability system ensuring both the openness and security of transaction information, facilitating independent product information sharing and matching. Cao *et al.* [28] demonstrate the influence of blockchain-based platforms on decision-making among AFSC members, revealing that such platforms can enhance consumer trust and increasing supply chain yield and profitability. Additionally, Liu *et al.* [29], Chen *et al.* [30], and Li *et al.* [31] examine the impact of blockchain technology investment costs on the optimal decision-making and profitability of AFSC, addressing issues like freshness misreporting and moral hazard among logistics providers. Mukherjee *et al.* [32] calculate the global desirability index for traditional supply chains versus blockchain-enabled supply chains, highlighting the rationality of integrating blockchain technology into supply chain management to achieve sustainable development in agri-food supply chains. These studies collectively underscore the significant potential of blockchain technology in managing cost transparency, ensuring transparent transactions, and bolstering consumer confidence in green agri-foods, thereby contributing to the sustainable development of the GAFSC.

III. Problems Description and Model

A. Problems Description

Game theory serves as a fundamental tool for investigating decision-making challenges within supply chains. It effectively captures the interplay of various factors, including costs, demand, and benefits, in the decision-making processes of supply chain members [33]. Therefore, this paper utilizes Stackelberg game theory to analyze and introduce a GAFSC model (as depicted in Fig. 1) encompassing a manufacturer, logistics provider, and retailer, with the retailer assuming the leadership role. The process commences with production, categorization, and initial processing of green agri-foods by the manufacturer. Subsequently, the logistics provider preserves, stores, and transport these products, which are then sold by retailers to consumers. In this study, we investigated the application of blockchain technology within the GAFSC, leveraging its decentralized, open, and immutable attributes to facilitate transparent management of cost information. This approach is aimed at countering misreporting behavior by the manufacturer and logistics provider, thereby mitigating the adverse effects of cost information constraints.

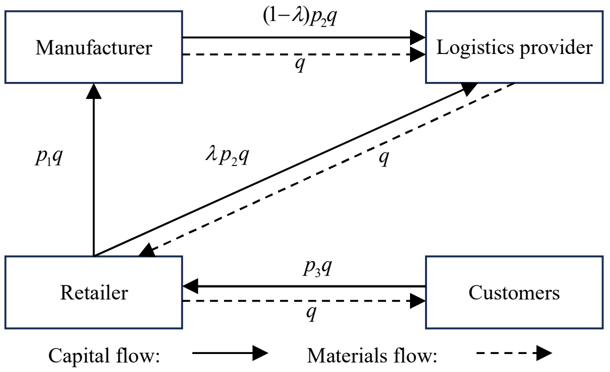


Fig. 1. The green agri-food supply chain model.

TABLE I presents a comprehensive summary of all the symbols used in this paper and their corresponding meanings.

TABLE I
DESCRIPTION OF THE SYMBOLS

Symbol	Description
T	The longest sales cycle of green agri-foods.
$\kappa(t)$	Freshness of the products at t, $\kappa=\hat{\kappa}$, when $t=0$.
α	Elasticity coefficient of the loss of freshness.
θ	Elasticity coefficient of the preservation cost.
g	Green degree of the product.
h	Elasticity coefficient of the green cost.
$q(t)$	Market demand at t.
A	Potential market demand.
b	Elasticity coefficient of the retail price.
ρ	Elasticity coefficient of the green degree.
β	Elasticity coefficient of the freshness.
p_1	The wholesale price charged by the manufacturer to the retailer.
Δp_1	The retail price markup, the retailer adds Δp_1 to the wholesale prices and sells them to customers.
p_2	The transportation price charged by the logistics provider to the manufacturer and the retailer.
p_3	The retail price charged by the retailer to consumers.
i	The subscript i denotes manufacturer, logistics provider, and retailer, $i=1, 2, 3$.
c_i	Operating cost of member i.
c_B	Application cost of blockchain technology.
γ	Optimization coefficient of c_3.
μ, η	Misreporting coefficient of the cost of manufacturer and logistics provider.
λ	Transportation cost-sharing ratio of the retailer.
j	The superscript j denotes the application of blockchain technology, n denotes no application, and y denotes application.
π_i^j	Profit of member i in j model.
ε	Random error, $\varepsilon \sim N(0, \sigma^2)$.

B. Model Assumptions

Assumptions 1: The natural freshness decay process of green agri-foods can be represented by the equation $\kappa(t)=\hat{\kappa}-\alpha\sqrt{t/T}$. The logistics provider bears the responsibility for product preservation, incurring a cost denoted by $\theta\hat{\kappa}^2/2$, where $\hat{\kappa}>0$, $\alpha>0$, $\theta>0$, $0\le t\le T$. The green cost is represented as $hg^2/2$, where $g>0$, $h>0$.

This assumption is based on prior research conducted by Wen *et al.* [34] and Liu [35].

Assumptions 2: Market demand for green agri-foods is influenced by factors such as price, degree of greenness, and freshness. Consumer demand can be expressed as follows: $q(t)=A-bp_3+\rho g+\beta\kappa(t)+\varepsilon$, where $A>0$, $p_3>0$, $b>0$, $\rho>0$, $\beta>0$.

Assumptions 3: A retail price markup contract prevents manufacturers and logistics providers from increasing markup excessively based on their cost information advantage. In this arrangement, the retailer adds Δp_1 to the wholesale prices and sells products to customers. The contract is defined as $p_3=p_1+\Delta p_1$, where $p_1>0$, $\Delta p_1>0$. The market demand is:

$$q(t)=A-b(p_1+\Delta p_1)+\rho g+\beta\kappa(t)+\varepsilon \quad (1)$$

This assumption is primarily based on the research results of Feng *et al.* [36].

Assumptions 4: Adopting blockchain technology in the GAFSC by the retailer mitigates the impact of cost information constraints on the supply chain and reduces transaction time and costs [37]. Therefore, the retailer operating cost decreases from c_3 to γc_3, where $0<\gamma<1$.

IV. Model Solution and Discussion

This section explores the optimal decision-making strategies of the GAFSC before and after the application of blockchain technology. Within the Stackelberg game led by the retailer, members of the GAFSC make sequential decisions. First, the retailer forecasts market demand based on consumer behavior and determines the optimal order quantity while considering the reactions of the manufacturer and logistics provider. Accordingly, the logistics provider decides prices based on order quantity and transportation costs. Finally, the manufacturer sets wholesale prices based on production costs and order quantities.

A. Basic Decision Model of the GAFSC

We examined the potential for the misreporting behavior of manufacturers and logistics providers with access to cost information and analyzed the possible impact of such behavior on the GAFSC's decision-making process.

The retailer's determination is as follows:

$$\max_{\Delta p_1^n,\, q^n} \pi_3^n = (\Delta p_1^n - \lambda^n p_2^n - c_3) q^n(t) \tag{2}$$

The logistics provider's determination is as follows:

$$\max_{p_2^n,\, \eta^n} \pi_2^n = [p_2^n - (1+\eta^n)c_2] q^n(t) - \theta \hat{\kappa}^2 / 2 \tag{3}$$

The manufacturer's determination is as follows:

$$\max_{p_1^n,\, \mu^n} \pi_1^n = [p_1^n - (1-\lambda^n) p_2^n - (1+\mu^n)c_1] q^n(t) - hg^2 / 2 \tag{4}$$

The reverse induction method is employed to solve the model. For a given retail price markup Δp_1 and logistics provider transportation price p_2, $\partial^2 \pi_1^n(p_1^n) / \partial (p_1^n)^2 = -2b < 0$, which indicates that the optimal decision of the manufacturer exists. Then, by solving $\partial \pi_1^n(p_1^n) / \partial p_1^n = 0$, the optimal wholesale price function can be obtained:

$$p_1^n(\Delta p_1, p_2) = \frac{A - b[\Delta p_1 - (1-\lambda)p_2 - (1+\mu)c_1] + \rho g + \beta \kappa(t)}{2b} \tag{5}$$

By substituting (5) into (3), $\partial^2 \pi_2^n(p_2^n) / \partial (p_2^n)^2 = -b(1-\lambda) < 0$ can be obtained. Based on this result, the logistics provider should make the following optimal decision:

$$p_2^n(\Delta p_1) = \frac{A - b[\Delta p_1 + (1+\mu)c_1 - (1-\lambda)(1+\eta)c_2] + \rho g + \beta \kappa(t)}{2b(1-\lambda)} \tag{6}$$

Similarly, substituting (5) and (6) into (2) yields the optimal decision of the retailer is as follows:

$$\Delta p_1^{n*} = \frac{A - b[(1+\mu)c_1 + (1-\lambda)^2(1+\eta)c_2 - (1-\lambda)c_3] + \rho g + \beta \kappa(t)}{b(2-\lambda)} \tag{7}$$

Therefore, the optimal decision-making for the GAFSC before the implementation of blockchain technology can be determined as follows:

$$p_1^{n*} = \frac{3(1-\lambda)A + b[(5-\lambda)(1+\mu)c_1 + (1-\lambda)(5-4\lambda)(1+\eta)c_2 - 3(1-\lambda)c_3] + 3(1-\lambda)\rho g + 3(1-\lambda)\beta \kappa(t)}{4b(2-\lambda)} \tag{8}$$

$$p_2^{n*} = \frac{A - b[(1+\mu)c_1 - (3-2\lambda)(1+\eta)c_2 + c_3] + \rho g + \beta \kappa(t)}{2b(2-\lambda)} \tag{9}$$

$$p_3^{n*} = \frac{(7-3\lambda)A + b(1-\lambda)[(1+\mu)c_1 + (1+\eta)c_2 + c_3] + (7-3\lambda)\rho g + (7-3\lambda)\beta \kappa(t)}{4b(2-\lambda)} \tag{10}$$

$$q^{n*} = \frac{(1-\lambda)\{A - b[(1+\mu)c_1 + (1+\eta)c_2 + c_3]\} + \rho g + \beta \kappa(t)}{4(2-\lambda)} \tag{11}$$

Substituting (7)-(11) into (2)-(4) yields the optimal profit of the each member as follows:

$$\pi_1^{n*} = \frac{\{(1-\lambda)A + b\{[(7-3\lambda)(1+\mu) - 4(2-\lambda)]c_1 + (\lambda-1)(1+\eta)c_2 + (\lambda-1)c_3\} + (1-\lambda)\rho g + (1-\lambda)\beta \kappa(t)\}\{(1-\lambda)\{A - b[(1+\mu)c_1 + (1+\eta)c_2 + c_3]\} + \rho g + \beta \kappa(t)\} - 32b(2-\lambda)^2 hg^2}{16b(2-\lambda)^2} \tag{12}$$

$$\pi_2^{n*} = \frac{(1-\lambda)\{A - b[(1+\mu)c_1 + [2(2-\lambda) - (3-2\lambda)(1+\eta)]c_2 + c_3] + \rho g + \beta \kappa(t)\}\{A - b[(1+\mu)c_1 + (1+\eta)c_2 + c_3] + \rho g + \beta \kappa(t)\} - 4b(2-\lambda)^2 \theta \hat{\kappa}^2}{8b(2-\lambda)^2} \tag{13}$$

$$\pi_3^{n*} = \frac{(1-\lambda)\{A - b[(1+\mu)c_1 + (1+\eta)c_2 + c_3] + \rho g + \beta \kappa(t)\}^2}{8b(2-\lambda)} \tag{14}$$

Proposition 1: In the traditional GAFSC led by the retailer, the degree of cost misreporting by the manufacturer is directly related to the wholesale and retail prices of the product and inversely related to the transportation price and order quantity. Conversely, the extent of cost misreporting by the logistics provider is directly linked to the wholesale, transportation, and retail prices, and inversely connected to the order quantity.

Proof: According to (8)-(11), we can calculate $\partial p_1^{n*} / \partial \mu = (5-\lambda)c_1 / [4(2-\lambda)] > 0$, $\partial p_2^{n*} / \partial \mu = -c_1 / [2(2-\lambda)] < 0$, $\partial p_3^{n*} / \partial \mu = (1-\lambda)c_1 / [4(2-\lambda)] > 0$, $\partial q^{n*} / \partial \mu = -(1-\lambda)bc_1 / [4(2-\lambda)] < 0$, then p_1^{n*} and p_3^{n*} increase with the increase of μ, p_2^{n*} and q^{n*} decrease. Similarly, $\partial p_1^{n*} / \partial \eta > 0$, $\partial p_2^{n*} / \partial \eta > 0$, $\partial p_3^{n*} / \partial \eta > 0$, $\partial q^{n*} / \partial \eta < 0$, then p_i^{n*} increase with the increase of η, and q^{n*} decreases. Thus, Proposition 1 is proved.

This conclusion highlights that the cost misreporting conduct of both the manufacturer and logistics provider in the GAFSC significantly influences the decision-making of its members. Specifically, their misreporting behavior consistently affects order quantity and wholesale and retail prices while exerting an opposing effect on transportation costs. Members exploit their cost information advantage to obscure actual costs, creating a false perception of high costs. Greater misreporting intensifies the burden on retailers and consumers for green agri-foods. Exaggerated production and transportation costs translate directly into inflated wholesale and transportation prices. According to demand theory, this leads to a decrease in market demand.

Proposition 2: In this supply chain, manufacturers and logistics providers maximize profits by misreporting production and transportation costs. The optimal coefficients of misreporting, μ and η, can be obtained as follows:

$$\mu^{n*} = \frac{(3-\lambda)f_1}{(9-5\lambda)bc_1}, \quad \eta^{n*} = \frac{2(1-\lambda)f_1}{(9-5\lambda)bc_2} \tag{15}$$

Proof: We can calculate from (12)-(14) that $\partial^2 \pi_1^{n*} / \partial \mu^2 < 0$ and $\partial^2 \pi_2^{n*} / \partial \eta^2 < 0$. The maximum values of the two parameters exist. By combining $\partial \pi_1^{n*} / \partial \mu = 0$ and $\partial \pi_2^{n*} / \partial \eta = 0$, where $f_1 = A - b\sum c_i + \rho g + \beta \kappa(t)$, we obtain (15). The conclusion of Proposition 2 is proved.

The manufacturer and logistics provider misreport costs to create a perception of high costs, thereby boosting profits and facilitating the acceptance of product price increases by the retailer. It can be inferred from equation that the optimal misreporting coefficients μ^{n*} and η^{n*} decrease as c_i, g, and κ increase. In particular, μ^{n*} increases with λ, whereas η^{n*} decreases. This suggests that an elevation in the greenness, freshness, and cost of agri-foods can reduce the extent of cost misreporting by the manufacturer and logistics provider, as higher costs limit the opportunities for misreporting behavior. The manufacturer, who bear a smaller share of transportation costs, have a greater information advantage when it comes to misreporting production costs, as their deceptive practices are more easily concealed.

Proposition 3: In this supply chain, the increase in the misreporting coefficient of production cost μ, initiates a rise in the manufacturer's profit, followed by a decline, while the profits of the retailer, logistics provider, and the overall supply chain gradually decrease. Similarly, with an increase in the misreporting coefficient of transportation cost η, the logistics provider's profit first ascends and then falls. Simultaneously, the profits of both the retailer and manufacturer decrease, along with other participants in the supply chain.

Proof: We can obtain the second derivative of π_1^{n*} and π_2^{n*} about μ and η from the proof of Proposition 2. $\partial\pi_2^{n*}/\partial\mu<0$, $\partial\pi_3^{n*}/\partial\mu<0$, $\partial\sum\pi_i^{n*}/\partial\mu<0$, $\partial\pi_1^{n*}/\partial\eta<0$, $\partial\pi_3^{n*}/\partial\eta<0$, and $\partial\sum\pi_i^{n*}/\partial\eta<0$. When the coefficient of misreported manufacturer's cost μ increases, π_1^{n*} initially increases and then decreases, while π_2^{n*}, π_3^{n*}, and $\sum\pi_i^{n*}$ decrease. Similarly, when the coefficient of misreported logistics provider's cost η increases, π_2^{n*} initially increases and then decreases, while π_1^{n*}, π_3^{n*}, and $\sum\pi_i^{n*}$ decrease. Finally, Proposition 3 is established.

In transactions involving green agri-foods, where the retailer holds decision-making authority, the manufacturer and logistics provider might leverage their cost information advantages to counterbalance negotiation weaknesses. This can result in an exaggeration of costs and increased prices for products and services, as they strive to maximize profits as rational economic actors. However, the core of this behavior lies in appropriating the profits of other members to attain their objectives, thereby exacerbating information asymmetry and eroding both their own profits and the operational efficiency of the GAFSC.

B. Blockchain Investment Decision Model of the GAFSC

This section discusses the retailer's adoption of blockchain technology for transparent cost information management. This entails tracking, gathering, and validating production and transportation costs to dissuade the manufacturer and logistics provider from resorting to misreporting practices. We explored the direct influence of technology investment costs on profits and its influence on the retailer's decision to adopt blockchain technology. In particular, we assessed the investment prerequisites for the retailer to embrace blockchain technology and its effects on optimal decision-making and member profitability before and after implementation.

The retailer's determination is as follows:

$$\max_{\Delta p_1^y,\, q^y} \pi_3^y = (\Delta p_1^y - \lambda^y p_2^y - \gamma c_3 - c_B) q^y(t) \quad (16)$$

The logistics provider's determination is as follows:

$$\max_{p_2^y} \pi_2^y = (p_2^y - c_2) q^y(t) - \theta\hat{\kappa}^2/2 \quad (17)$$

The manufacturer's determination is as follows:

$$\max_{p_1^y} \pi_1^y = [p_1^y - (1-\lambda^y)p_2^y - c_1] q^y(t) - hg^2/2 \quad (18)$$

Similarly, the optimal decision for GAFSC can be obtained as follows:

$$\Delta p_1^{y*} = \frac{A - b[c_1 + (1-\lambda)^2 c_2 - (1-\lambda)\gamma c_3 - (1-\lambda)c_B] + \rho g + \beta\kappa(t)}{b(2-\lambda)} \quad (19)$$

$$p_1^{y*} = \frac{3(1-\lambda)A + b[(5-\lambda)c_1 + (1-\lambda)(5-4\lambda)c_2 - 3(1-\lambda)\gamma c_3 - 3(1-\lambda)c_B] + 3(1-\lambda)\rho g + 3(1-\lambda)\beta\kappa(t)}{4b(2-\lambda)} \quad (20)$$

$$p_2^{y*} = \frac{A - b[c_1 - (3-2\lambda)c_2 + \gamma c_3 + c_B] + \rho g + \beta\kappa(t)}{2b(2-\lambda)} \quad (21)$$

$$p_3^{y*} = \frac{(7-3\lambda)A + b(1-\lambda)(c_1 + c_2 + \gamma c_3 + c_B) + (7-3\lambda)\rho g + (7-3\lambda)\beta\kappa(t)}{4b(2-\lambda)} \quad (22)$$

$$q^{y*} = \frac{(1-\lambda)[A - b(c_1 + c_2 + \gamma c_3 + c_B)] + \rho g + \beta\kappa(t)}{4(2-\lambda)} \quad (23)$$

By substituting (19)-(23) into (16)-(18) and performing calculations, the optimal profits for each member are given by:

$$\pi_1^{y*} = \frac{\{(1-\lambda)[A - b(c_1 + c_2 + \gamma c_3 + c_B) + \rho g + \beta\kappa(t)]\}^2 - 8b(2-\lambda)^2 hg^2}{16b(2-\lambda)^2} \quad (24)$$

$$\pi_2^{y*} = \frac{(1-\lambda)[A - b(c_1 + c_2 + \gamma c_3 + c_B) + \rho g + \beta\kappa(t)]^2 - 4b(2-\lambda)^2\theta\hat{\kappa}^2}{8b(2-\lambda)^2} \quad (25)$$

$$\pi_3^{y*} = \frac{(1-\lambda)[A - b(c_1 + c_2 + \gamma c_3 + c_B) + \rho g + \beta\kappa(t)]^2}{8b(2-\lambda)} \quad (26)$$

Proposition 4: The implementation of blockchain technology results in reduced profits for the GAFSC's manufacturer, logistics provider, and retailer due to increased technology investment costs.

Proof: According to (26), we can obtain the first derivative of π_3^{y*} about c_B:

$$\frac{\partial\pi_3^{y*}}{\partial c_B} = -\frac{(1-\lambda)[A - b(c_1 + c_2 + \gamma c_3 + c_B) + \rho g + \beta\kappa(t)]}{4(2-\lambda)} \quad (27)$$

Because $\partial\pi_3^{y*}/\partial c_B<0$, the higher the investment cost c_B of this technology, the lower the retailer's profit π_3^{y*}. Similarly, $\partial\pi_1^{y*}/\partial c_B<0$ and $\partial\pi_2^{y*}/\partial c_B<0$ indicate that increased blockchain technology investment costs decrease the profits of the logistics provider and manufacturer. Therefore, Proposition 4 is substantiated.

Proposition 4 assumes that increasing the investment in blockchain technology inevitably diminishes the profits of the GAFSC members. While the application of this technology can address practical issues, it also incurs additional fundamental expenses. Nevertheless, the focus should not solely be on intuitive profit loss; rather, we need to assess whether implementing this technology can mitigate profit losses stemming from conventional cost information constraints and ultimately bolster actual profits.

Proposition 5: In the green agri-food supply chain, when the investment cost of blockchain technology satisfies the condition $c_B < \bar{c}_B$, the retailer can deploy this technology to counteract the cost misreporting behavior of the manufacturer and logistics provider, thereby preventing losses. When $c_B < \tilde{c}_B$, the implementation of the technology leads to increased profits for logistics providers. When $c_B < \hat{c}_B$, blockchain technology can enhance operational efficiency and profitability across the entire supply chain where $\hat{c}_B < \tilde{c}_B < \bar{c}_B$.

Proof: Without the implementation of blockchain technology, a retailer's profits might be negatively impacted by cost misreporting from manufacturers and logistics providers. However, the adoption of this technology could increase the retailer's costs. Therefore, the retailer must ensure their profits increase after the implementation of blockchain technology (i.e., $\pi_r^{y*} > \pi_r^{n*}$). By substituting (14) and (26) into it, the boundary value for retailer investment can be determined as follows:

$$c_B < \mu c_1 + \eta c_2 + (1-\gamma)c_3 \tag{28}$$

Then, by substituting (15) into (28), the investment condition is given by:

$$c_B < \frac{(5-3\lambda)f_1}{(9-5\lambda)b} + (1-\gamma)c_3 \tag{29}$$

TABLE II presents a comparison of the profits earned by each member of the GAFSC before and after the implementation of blockchain technology, where $\bar{c}_B = (5-3\lambda)f_1/(9-5\lambda)b + (1-\gamma)c_3$, $\tilde{c}_B = [f_2 - 2(2-\lambda)\sqrt{(3-2\lambda)f_1/(9-5\lambda)}]/b$, $\hat{c}_B = \{f_2 - 2(2-\lambda)\sqrt{17-9\lambda}f_1/[(9-5\lambda)\sqrt{7-3\lambda}]\}/b$, $f_2 = A - b(c_1 + c_2 + \gamma c_3) + \rho g + \beta\kappa(t)$. Thus, Proposition 5 is proved.

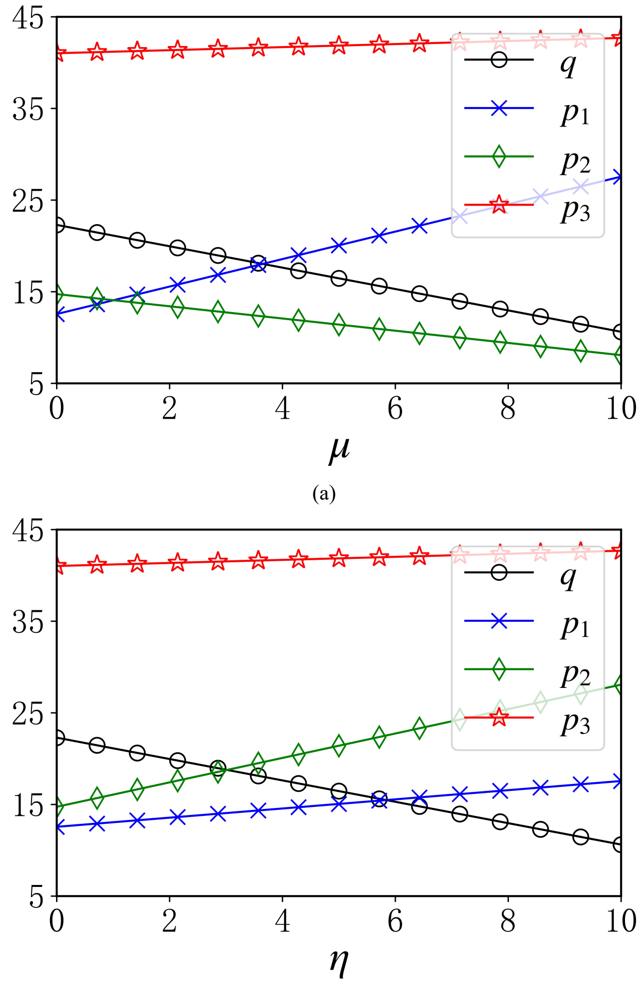
TABLE II
PROFIT COMPARISON BEFORE AND AFTER BLOCKCHAIN TECHNOLOGY APPLICATION

Condition	$\sum\pi_i$	π_1	π_2	π_3
$0 < c_B < \hat{c}_B$	+	−	+	−
$\hat{c}_B \le c_B < \tilde{c}_B$	−	−	+	−
$\tilde{c}_B \le c_B < \bar{c}_B$	−	−	−	−
$c_B \ge \bar{c}_B$	−	−	−	+

Proposition 5 regards the investment cost of blockchain technology as a crucial factor influencing the retailer's decision to adopt this technology. A reasonable investment cost can mitigate profit loss resulting from inaccurate information in the GAFSC. When the investment cost falls within a certain range, the retailer's profitability will rise as they actively adopt technology to attain cost transparency. However, excessive investment costs can burden the retailer and reduce profits if the benefits of technology adoption do not outweigh these costs.

V. Numerical Experiment

This section discusses numerical simulation experiments using Python 3.9 to analyze the effects of pertinent parameters on optimal decision-making and profit distribution among the members of the GAFSC. The aim is to demonstrate the reliability and practicality of the propositions. To ensure smooth experimentation, we referred to related research in this field and designated variables as follows: $T=5$, $t=2$, $A=300$, $b=7$, $c_i=2$, $\rho=6$, $\beta=5$, $\hat{\kappa}=1$, $g=0.9$, $\theta=2$, $h=5$, $\gamma=0.7$, $\lambda=0.5$, $\alpha=0.3$ accordingly. The simulation results are shown in Fig. 2-5.

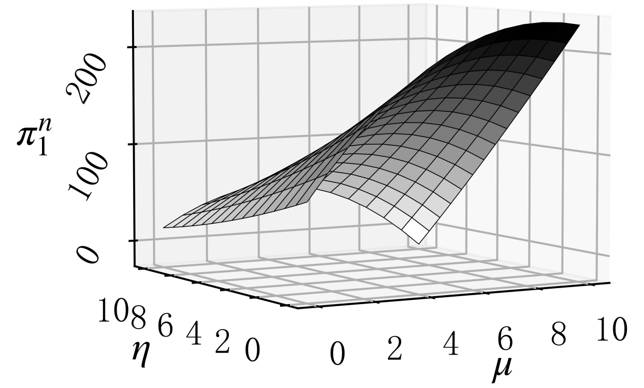


(a)

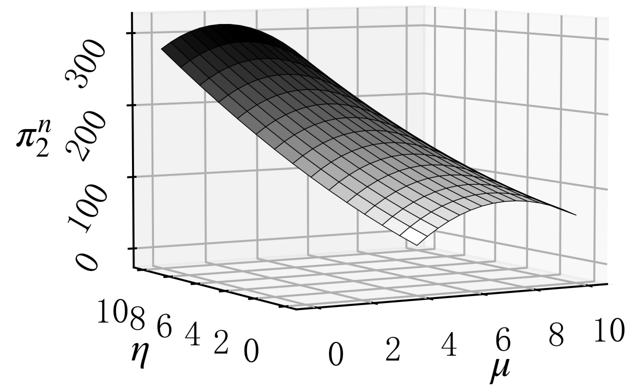
(b)

Fig. 2. Effects of misreporting coefficients on decision making.

Fig. 2 illustrates the effects of misreporting costs by the manufacturer and logistics provider on decision-making within the GAFSC without blockchain technology. It demonstrates that as the degree of cost misreporting increased, wholesale and retail prices for agri-foods escalated, while market demand decreased. Members of this supply chain acted in their own self-interest, and exaggerating costs led to an increase in the wholesale price of agri-foods. This was because the profit gained by manufacturers and logistics providers outweighed any potential losses caused by a decrease in market demand. The misreporting behavior of the manufacturer and logistics provider had an inverse relationship with transportation costs for agri-foods while being directly proportional to μ, and inversely proportional to η. Because of the direct influence of the logistics provider's exaggerated costs on transportation prices, and the increasing effect of cost misreporting with the degree of misreporting, the impact of the logistics provider's cost misreporting behavior on transportation prices was greater than that of the manufacturer, aligning with Proposition 1.



(a)



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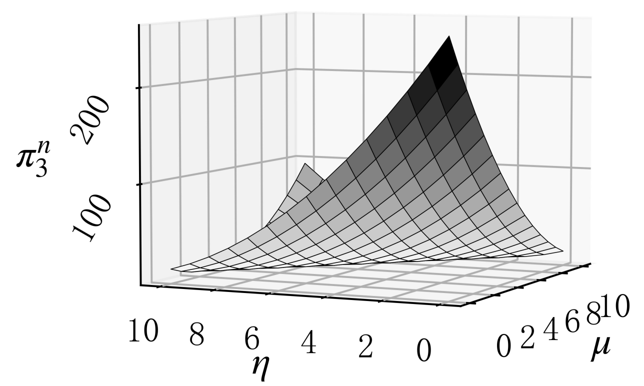

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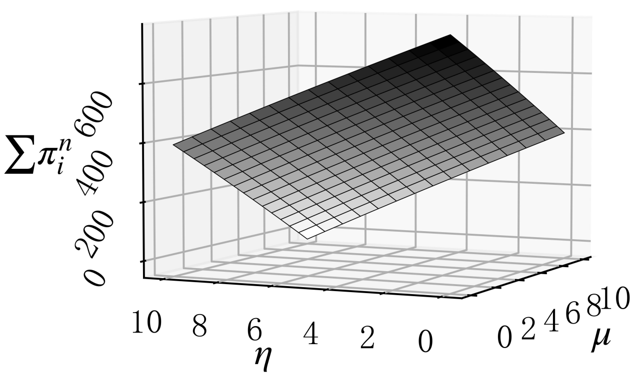
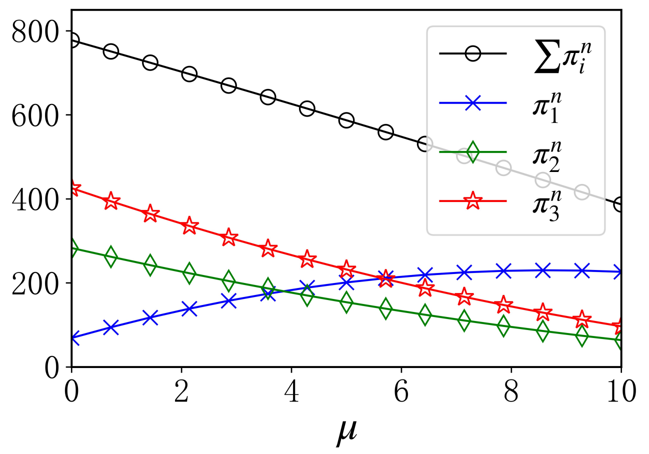


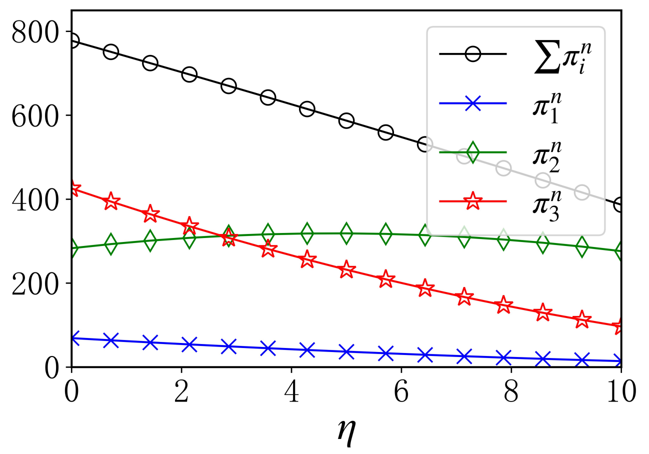
(d)

Fig. 3. The trend in profit changes resulting from misreporting.

As illustrated in Fig. 3, the impact of cost misreporting behavior by both the manufacturer and logistics provider on profit distribution. Fig. 3(a) reveals that the manufacturer's profit initially increased but subsequently decreased with an increase in the degree of cost misreporting, whereas it decreased with an increase in the degree of cost misreporting by the logistics provider. According to (15), the optimal cost misreporting coefficient for the manufacturer in the GAFSC was $\mu^{n*}=7.54$, indicating that the manufacturer engaged in cost misreporting behavior to compensate for decision-making weaknesses and enhance profits. Similarly, we determined that the logistics provider's optimal cost misreporting coefficient was $\eta^{n*}=3.02$, which was consistent with Proposition 2. Based on Fig. 3(c), the retailer's profit declined as the degree of misreporting behavior increased for either the manufacturer or logistics provider, particularly when one member had a low level of misreporting. Conversely, if one member exhibited a high degree of misreporting, an increase in the other member's misreporting attenuated the impact of the former's misreporting, and at this point, the latter's exaggerated cost was more advantageous for the retailer. Refraining from misreporting behavior was crucial for maintaining the cost-effectiveness of information collection in supply chain management. Any attempt to manipulate cost reporting, whether by manufacturers or logistics providers, inevitably resulted in reduced the profitability and operational efficiency of the GAFSC.



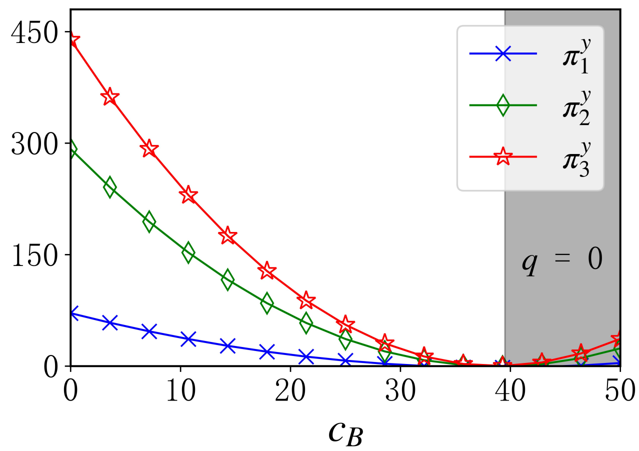
(a)



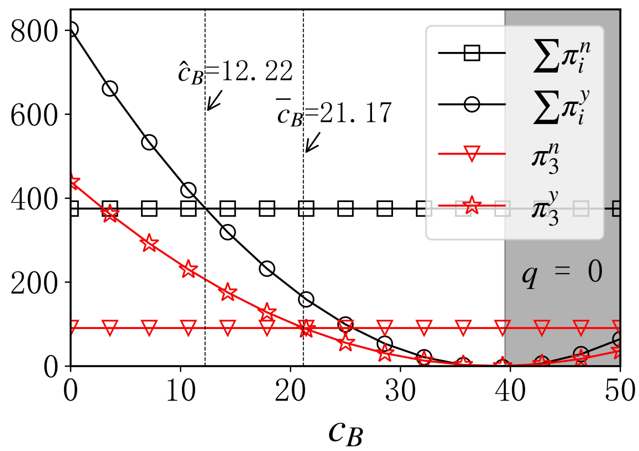
(b)

Fig. 4. Effects of misreporting coefficients on profitability.

Fig. 4 illustrates the effects of misreporting production and transportation costs on the GAFSC's profit distribution. The profitability of the cost-misreporting member first increased and then decreased with the degree of misreporting, whereas other members' profits and the system's overall profits declined. Therefore, the manufacturer and logistics provider each contribute an optimal misreporting coefficient and increase the wholesale and transportation price of products misreporting costs. Both the manufacturer and logistics provider tend to misreport their costs to maximize profits, confirming Proposition 3.



(a)



(b)

Fig. 5. Effects of profits before and after the implementation of blockchain technology.

As depicted in Fig. 5(a), the profits of the manufacturer, logistics provider, and retailer decrease as the investment cost for blockchain technology increases. The increased investment cost is an additional cost burden. Members in the supply chain induce cost pressures by increasing prices, causing a decrease in market demand. When costs exceed the critical value, orders for green agri-foods are reduced to 0 and transactions are terminated. As illustrated in Fig. 5(b), the retailer's profit and the overall profit decrease as the investment cost for blockchain technology increases, with an identifiable critical value for investment. When $c_B < \bar{c}_B = 21.17$, the integration of blockchain technology for cost management enhances the retailer's profitability and incentivizes investment in this technology. Meanwhile, when $c_B < \hat{c}_B = 12.22$, the total profit of the supply chain increases with the application of blockchain technology. Thus, lower investment costs not only benefit the retailer but also mitigate losses among other members due to cost misreporting while enhancing the overall profitability and operational efficiency. The implementation of blockchain technology holds promise in enhancing information transparency, curbing information collection costs, and refining decision-making efficiency in the GAFSC, thereby affirming Propositions 4 and 5.

VI. Conclusion

In this study, we applied Stackelberg game theory to investigate the ramifications of cost misreporting by manufacturers and logistics providers on optimal decision-making and profit distribution in a three-tier green agri-food supply chain led by retailers. Subsequently, we introduced blockchain technology to circumvent the cost information constraints within this chain, thereby alleviating profit losses resulting from misreporting behavior. We also delved into the critical investment cost threshold of this technology and its effects on decision-making and profit outcomes before and after implementation, with the overarching goal of enhancing the decision-making efficiency of the GAFSC.

The study has resulted in several notable conclusions, contributing to the existing literature. In the traditional green agri-food supply chain, manufacturers and logistics providers employ cost manipulation to offset their negotiation disadvantages in transactions. Notably, the extent of cost misreporting by manufacturers is directly correlated with the wholesale and retail prices of green agri-foods and inversely proportional to transportation costs and market demand. Similarly, the degree of cost misreporting by logistics providers is directly tied to wholesale, transportation, and retail prices but is inversely related to market demand.

Furthermore, before implementing blockchain technology, manufacturers and logistics providers tended to inflate their costs to counterbalance their market disadvantages and increase profits. This behavior can be represented by distinct optimal misreporting coefficients μ^{n*} and η^{n*}. Essentially, the practice hinges on reaping profits at the expense of other supply chain members, ultimately diminishing returns, imposing additional burdens, increasing information collection costs, and complexity within the supply chain, thereby reducing the operational efficiency of the GAFSC and hindering the realization of its objectives.

Lastly, following the integration of blockchain technology, the profitability of retailers, logistics providers, manufacturers, and the entire supply chain depends on the investment cost of the technology and each member's individual costs. Lower technology investment costs translate to reduced additional expenses for each member, resulting in higher profits. A relationship threshold exists between the profits of retailers, logistics providers, the entire supply chain, and the investment cost of blockchain technology. Each member can only tolerate a maximum investment cost if this threshold remains lower than their respective technology's investment cost. This condition is vital for realizing profit increments through technology implementation.

Whereas our study sheds valuable light on the potential of blockchain technology for cost transparency management in the GAFSC, practical implementation remains limited. The application of blockchain technology in supply chain management remains in its exploratory stages and falls short of achieving full-chain integration, information sharing, and data reliability. Substantial practical experience is requisite to facilitate integrating and advancing emerging technologies like blockchain in the agri-food industry. Additionally, further research is warranted to ascertain the equitable allocation of implementation and maintenance expenses associated with blockchain technology among the members of the GAFSC.

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