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Research on the influencing factors of traceability information sharing of agricultural product supply chain under the background of blockchain

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A B S T R A C T

Increasing customer apprehensions regarding the security and nutritional value of agricultural goods are compelling governments and industries to implement traceable, transparent, and reputable logistics management systems. Blockchain-based agricultural logistics management systems guarantee the permanence of data once it is uploaded but cannot cope with the risk of data being falsified before uploading to the blockchain. In this work, we developed a collaborative game model between government bodies and agricultural enterprises based on the evolutionary game theory and explored the influencing factors of enterprises following the rules to share the real traceability information through numerical simulation using MATLAB. The findings show that government incentives and penalties promote positive behavior, and consumer and media supervision contribute to supply chain transparency, but firms tend to share truthful information only when it benefits them. This study builds upon existing research on the impact of social variables on both members' decision-making behavior. It highlights the positive roles of consumers and the media in the supervision of agricultural product traceability, which can help to raise public awareness of social responsibility and thus promote positive interaction in the market.

1. Introduction

In the context of globalization, agricultural products, as an important economic pillar of many countries and regions, have a direct bearing on agricultural output and the development of the national economy in terms of quality control. Simultaneously, agricultural commodities, as an essential source of food for human beings in their daily lives, are intimately connected to the lives and wellbeing of individuals. However, the frequency of agricultural safety incidents around the world indicates that this is not just a problem for a specific country or region, but one that is faced universally. For example, in 2018, there was an outbreak of contamination of rapeseed in Europe, where imports from Ukraine were suspected of being adulterated with a hazardous substance-2,3-dichloro-1,4-benzenedicarboxylate (DCD). DCD is a chemical used for soil management and is not approved for food production in the EU and elsewhere. This discovery resulted in the recall and destruction of affected agricultural products in several European countries, causing a significant disruption to the European agricultural market. In 2021, India was exposed to a series of incidents of excessive pesticide residues in agricultural products. This incident involved a wide range of products, including fruits (e.g. apples, strawberries, etc.), vegetables (e.g. tomatoes, eggplants, etc.), and grains (e.g. rice, wheat, etc.). These agricultural products have been detected with pesticide residues exceeding health standards or legal limits, and in some cases exceeding safety limits, causing certain impacts on farmers and the agricultural industry in India, these difficulties include a decrease in the number of agricultural products being exported and fluctuations in the prices of agricultural products. The occurrence of these incidents shows that the reliability and security of agricultural goods are not solely a topic of national interest, but also a global issue that requires the joint efforts of the international community to ensure food safety.

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A traceability system is one of the best solutions to the present problems with both the security and the quality of agricultural products. This will help to improve the supply chain and ensure that consumers can have confidence in the products they buy. By monitoring and tracing the whole process of production, processing and circulation of products, the agriculture supply chain's traceability system can help the supervisory authorities discover potential risk factors in time, take preventive measures in advance, and strengthen the control over the safety of agricultural products. Once a quality problem occurs, the traceability system can quickly locate the specific link and batch where the problem occurred, which helps to quickly handle and solve the problem and prevent it from expanding. To meet national development and people's needs, the government and enterprises are looking at how to use technological innovations to address the challenge of full traceability of agricultural products (Feng et al., 2020). Currently, blockchain technology, a digital technology that has already begun to change and reshape the relationships between agricultural ecosystems (Galvez et al., 2018). Based on distributed storage, peer-to-peer transmission, consensus mechanisms, encryption algorithms, and other key technologies, its features are decentralization and data non-tampering (Zhang et al., 2021a), which can efficiently tackle the issue of confidence in transmitting data between each side of the supply chain. It establishes a reliable transaction environment that meets the standards for traceability. However, initial information submitted to the blockchain cannot be guaranteed to be authentic by blockchain technology. Some members of the supply chain still lie for additional benefits, which makes the cost of verifying and monitoring the authenticity of the initial information more expensive. This study aims to explore the influencing factors for companies to follow the rules to upload authentic traceability information, as well as to explore the long-term mechanism for traceability management in the agricultural supply chain and answer the following questions:

RQ (1): What are the key factors influencing the replication of dynamic systems comprising agricultural supply chain firms and governments?
RQ (2): Can consumer and media scrutiny combined with government create synergies to better ensure the safety of agricultural products?
RQ (3): What incentives and penalties should the government implement to regulate the safety of agricultural products?

2. Literature review

2.1 Research on the Application of Agricultural Traceability System Technology

The earliest methods of product traceability were manual production logs, which recorded the location and date of production and any other relevant information. However, there are many links involved in the circulation of agricultural products from production to the market, and it is difficult to summarize and integrate the subjects of each link and their data promptly, which leads to the problem of lack of trust among the participants in the process of product traceability (Zhang et al., 2021b). To address the challenge of ensuring the traceability of agricultural products, countries and regions are implementing technological solutions to enhance the traceability of these products throughout their life cycle, from production to consumption (Bhat et al., 2021; Li & Chen, 2023; Chen et al., 2014; Rawat et al., 2014; Xu et al., 2014). The earliest incarnation of RFID (Radio Frequency Identification) technology can be traced back to World War II, when it was used to identify friend and foe in aircraft (Landt, 2015). With the development and maturity of the technology, its application scope has gradually expanded to various fields such as retail, logistics, etc., providing an effective solution for realizing automatic identification and tracking of items. By embedding RFID tags in the packaging or labels of agricultural products, the tracking and management of products can be realized, and consumers can scan the tags and combine them with a database to obtain detailed information on planting locations, times (Alfian et al., 2020). However, Ruiz-Garcia et al. (2011) found in their study that the communication distance between RFID tags and readers is usually limited, depending on factors such as the frequency and power of the system as well as the environmental conditions, but even with HF and UHF systems, the read range is affected by factors such as object material and environmental interference. Xiong et al. (2013) found that WSN nodes can be used as relay nodes for RFID readers to transmit the read RFID tag data to a remote data aggregation point, and this WSN-RFID integrated system effectively improves the tag reading range and performance so that the tag data can be read by remote readers.

The notion of the Internet of Things has emerged because of the ongoing advancement of the Internet and the increasing prevalence of intelligent technologies. By connecting sensors, communication devices and the Internet, it realizes the interconnection and data exchange between various devices and enables the tracking of the complete life cycle of agricultural items (Whitmore et al., 2015; Ray, 2018). Very early on the Internet of Things system development, RFID tags were also included in the scope of IoT systems as sensing nodes of items. However, the practical application of RFID technology is still limited due to various technical and economic barriers. Costa et al. (2013) found that RFID technology requires additional hardware to standardize the management of information obtained from tags and readers. To further centralize the management of agricultural product data, it is proposed to integrate web-based cloud computing technology into IoT systems. Stergiou et al. (2018) also found that cloud computing eliminates the need for hardware devices as a technological service that provides access to information and data from anywhere at any time. Real-time monitoring, tracing and management of items can be realized through data transmission and processing of RFID readers and cloud servers. However, since IoT devices typically use low-power wireless communication technologies, such as low-power Bluetooth (BLE), Zigbee, or LoRa, these communication protocols typically do not support sophisticated encryption and authentication mechanisms, making the devices susceptible to unauthorized access or cyberattacks, which may result in data leakage, service interruption, or information tampering (Grimm et al., 2016; Zorzini et al., 2015; Hellani et al., 2021). At the same time, several scholars have pointed out that the immutability of information sharing is a prerequisite for realizing effective cooperation between participants in IoT systems, as well as an important factor for successful tracking of product data (García-Alcaraz et al., 2021; Wu et al., 2014; Lee et al., 2021). To address these challenges, Distributed Ledger Technology (DLT), especially blockchain technology, has been introduced to enhance trust and transparency in IoT systems. Blockchain networks use distributed storage, where each block contains the data of the current block as well as other metadata (e.g., timestamps and random numbers), and consensus mechanisms (e.g., proof of workload, proof of entitlement, etc.) are used to ensure that the data can't be tampered with by a single node(Zheng et al., 2018). With the arrival of the Web 3.0 era, in order to realize the vision of decentralization, user autonomy, and smart openness, Li et al. (2024) designed a smart blockchain technology architecture utilizing the amalgamation of artificial intelligence (AI) and blockchain technologies, which applies smart technology to all levels of the traditional blockchain architecture, so that the virtual technology and AI can be operated and interacted with in parallel, thus realizing more complex and smarter functions and applications. Although blockchain technology has demonstrated the potential to enhance the credibility of traceability, actual deployments of blockchain technology in the supply chain and logistics sector are still relatively scarce. By interviewing 18 companies in the supply chain sector, Kromes et al. (2024) found that most companies still have limited knowledge of blockchain technology, and only a small number of companies are aware that not investing in blockchain technology may cost them a competitive advantage.

2.2 Application of Evolutionary Game Theory in Traceability Management of Agricultural Products

Game theory is a mathematical tool and analytical framework that is widely used to study the behavior and outcomes of decisions made by participants in competitive or cooperative situations (Babu & Mohan, 2018). The participants in a game are called players, and each player has a set of choices of actions, which are called strategies. Each player receives a loss or gain at the end of the game, depending on their strategic choices and those of the other players. Players have varying degrees of information; some games are fully informative, where each player knows the strategies and payoff functions of the other players. Some games are imperfectly informative, where players can only make decisions based on the information they observe (Liu et al., 2016). Based on the above elements, game theory analyzes the outcome of the game by building a mathematical model. While game theory focuses on rational decision-making among individuals and reveals various possible behavioral outcomes in different situations, evolutionary game theory combines the concepts of game theory with genetic and evolutionary mechanisms and focuses more on cooperation among selfish individuals and the evolution of species adaptations (Askari et al., 2019). Evolutionary game theory explains the phenomena of cooperation, competition, and other behaviors observed in biological systems, and is therefore also known as the evolution of cooperation.

Traceability management of agricultural products involves multiple players in the supply chain, including farmers, producers, intermediaries, government regulators, and consumers (Demestichas et al., 2020). To guarantee the reliability and transparency of information throughout the production, processing, transportation, and marketing of agricultural products, the various participants need to cooperate. However, due to the existence of conflicting interests and asymmetrical resources and information among the various subjects, they frequently encounter numerous challenges and obstacles in practical application. In this case, each subject in the supply chain needs to coordinate their interests and seek relatively optimal solutions through gaming in an environment that affects each other (Kanda et al., 2008). Researchers have directed their attention to evolutionary game theory due to its high compatibility with this scenario.

Scholars hope that through the analysis of evolutionary game theory, they can better understand the cooperation and competition among the individuals in the supply chain, and further guide how to design reasonable incentives and management strategies, to enhance the successful execution of traceability management for agricultural products. Sujatha et al. (2018) used evolutionary game theory to analyze the behavioral patterns of supply chain participants and found that conflicts of interest among supply chain parties mainly stemmed from unstable cooperative relationships among members and information asymmetries. To further stabilize the cooperative relationship among supply chain members, Tan et al. (2019) used evolutionary game theory to analyze the evolutionary process of inter-firm information sharing cooperation under different punishment mechanisms and risk costs. The results show that increasing punishment and controlling costs to share risks can increase the probability of information sharing cooperation among supply chain firms. However, in the presence of information asymmetry, subjects in the supply chain may still choose to retain information or provide false information. Yinghua et al. (2018) created a model to show methods for facilitating the exchange of food safety information between food firms and government regulators. The model uses evolutionary game theory to show how different factors affect this process. The results show that government regulation can raise the caliber of information on food safety shared by enterprises and help maintain the efficiency and reliability of supply chain traceability management. Meanwhile, it is found that the power of government supervision is limited, and the solution to the problem of food safety information disclosure in the traceability system requires the synergistic cooperation between social supervision power and government supervision. To further optimize the way of information transfer and improve the trust between members, Peng et al. (2022) set up an evolutionary game model that shows how the interests of food factories, food suppliers, and customers affect each other, and showed through their analysis that strengthening governmental supervision and adopting incentives for consumers to file complaints can improve the trust between members of the food supply chain. Concentrating on how government control affects the safety and quality of agricultural goods, Li et al. (2023) explored the effect of government regulation on whether each stakeholder participates in quality regulation by constructing a three-party evolutionary game model of producers, supermarkets and e-commerce platforms. The findings point out that government regulation can incentivize stakeholders to participate faster and ultimately achieve quality and safety assurance in the agricultural supply chain (Semasinghe et al., 2014).

With the complexity of the agricultural supply chain, the adoption of technological means to improve traceability has become a common direction of efforts in various countries, and many studies have shown the possibility of blockchain technology to enhance and optimize the conventional traceability system for the supply chains of agricultural products. Evolutionary game theory provides a helpful tool for understanding the cooperative and competitive relationships among participants in a supply chain. By analyzing the evolutionary process of cooperation and potential conflicts of interest, researchers have proposed a series of incentive mechanisms and management strategies. However, the above studies still have some limitations:(1) Existing studies lack sufficient discussions on the potential of falsifying traceability information prior to uploading it to the blockchain. Therefore, this article aims to conduct a comprehensive examination of the risk associated with firms manipulating traceability information prior to uploading it onto the blockchain, and further provide feasible coping strategies and policy recommendations for decision makers in practice by exploring the motives behind the enterprises' behavior and the factors of the external environment. (2) Current research focuses mostly on the behavioral patterns and strategies of parties within the supply chain, and lacks adequate consideration of external environmental factors, such as consumer and media attention shaping public opinion and political pressure, which may directly affect corporate behavior and government regulation. Therefore, this study complements the model by introducing factors such as consumer attention and media reporting accuracy, focusing on the relationship between the public, firms and government, to explore a social governance model that is closer to the real circumstances and the demands of the people.

3. Game Model Analysis of Agricultural Supply Chain in the Context of Blockchain Technology

3.1 Model Assumptions and Establishment

The following assumptions are made regarding the interests and interactions between the government and agricultural enterprises in the traceability system of agricultural products for the construction of the game model of the two sides. The parameter symbols are presented in Table 1.

Hypothesis 1: Both the government and agribusiness are limited rational subjects (Zhu et al., 2007), Neither party has complete access to information pertaining to revenue decisions. The behavioral strategies selected by individuals are continuously learned and adapted to the choices of others in the game. In objective conditions, the goal of decision-making is to maximize their own interests (Kankam et al., 2023). The quality of information disseminated by firms is positively correlated with the dependability and safety of their offering (Lyu et al., 2023). The phenomenon of consumers purchasing produce that provides false traceability information is a consequence of the failure of government regulation.

Hypothesis 2: The government has the option to implement either strong or weak regulation, with the likelihood of selecting strict regulations represented by x and the likelihood of selecting gentle regulation represented by $1-x$. Agribusinesses can choose to share true information or share false information, with the likelihood of selecting to disclose true information represented by y and the likelihood of selecting to share false information denoted by $1-y$. where x, y satisfies: $0<x<1;0<y<1$.

Hypothesis 3: When the government participates in the supervision of the traceability system, it will choose its own supervision strength according to the supervision cost and difficulty. When choosing strong regulation, the government fulfills its own responsibilities and conducts regular spot checks, which can effectively reduce the probability of agricultural product safety accidents in the society and reduce the losses caused by agricultural product quality risks. However, it needs to pay more regulatory costs C_G, and the government will reap some social reputation benefits E_G after investigating and punishing a company's falsification of traceability information.

Hypothesis 4: Enterprises that upload traceability information to the blockchain can obtain the base reward E_C. When enterprises adopt the strategy of sharing true information, their sharing cost is C_T. When consumers pay attention to the traceability information of the products they buy, enterprises can obtain additional brand reputation benefits H_C from sharing true traceability information. However, it is also evident that enterprises may engage in speculative behaviors and will share false traceability information for their own benefit (Zhen et al., 2019), when the sharing cost is C_F.

Hypothesis 5: The probability that a consumer pays attention to the traceability information of the agricultural product purchased is denoted by α $(0 < \alpha < 1)$. Consumers will report to the government when products with false traceability information is found. In the event of a failure of government regulation, consumers will cease to utilize government reporting channels and instead turn to media platforms to expose products (Wu et al., 2020). In such instances, it can be posited that consumers and members of the media may be regarded as an independent third party capable of exerting regulatory pressure upon those in authority (Fang & Feng, 2022). But there are also distortions in media reports (e.g., consumers report incorrect information, competitors deliberately smear, etc.) (Clayton et al., 2020), let the probability that the media report the event accurately be β (0 < β < 1). The damage caused by media reports to organizations, including brand image degradation, customer claims, and loss of customers, were L_C; losses to the government, including penalties for dereliction of duty, loss of credibility, and damage to its reputation, amount to L_G.

Hypothesis 6: A firm that chooses the strategy of sharing false information will suffer a penalty loss of F if it is detected and investigated by the government regulator. The government will also provide an incentive R to the consumer if the consumer reports the exposure and successfully defends his rights.

Table 1
Model Parameter Settings and Meanings

Parameters	Meanings
x	Probability that the government chooses strong regulation
y	Probability that an agribusiness chooses to share true information
E_G	Prestige gains that can be gained from reducing risky accidents when governments choose strong regulation
C_G	The extra regulatory costs that governments need to pay when they choose strong regulation
E_C	Basic incentives received by agribusinesses for sharing information on the blockchain
H_C	Brand reputation gained from consumer attention when agribusinesses choose to share truthful information
C_T	Costs paid by agribusinesses choosing to share true information
C_F	Costs paid by agribusinesses choosing to share false information
P	Fines borne by agribusinesses when exposed or investigated for sharing false information
α	Probability of consumers choosing to focus on product traceability information
β	Probability that the media will accurately report the event
R	Government rewards for consumers reporting businesses sharing false information
L_C	Losses to agribusinesses because of media coverage, including brand image degradation, customer claims, and loss of customers
L_G	Damages caused by media reports to government regulators, including penalties for dereliction of duty, loss of credibility and damage to reputation

Both parties' mixed-strategy payoff matrices in the government-agribusiness game model built on the aforementioned assumptions are shown in Table 2.

Table 2
Mixed-strategy Payoff Matrix for Government and Agribusiness

Game Player	Government	
Agribusiness	strong regulation x	weak regulation $1-x$
sharing real information y	$E_G - C_G$, $E_C + \alpha H_C - C_T$	0, $E_C + \alpha H_C - C_T$
sharing false information $1-y$	$E_G + P - C_G$, $E_C - C_F - P$	$\alpha\beta(P - L_G - R)$, $E_C - C_F - \alpha\beta(P + L_C)$

3.2 Analysis of evolutionary stabilization strategies

The expected payoffs from different strategy choices of the government and agribusiness can be computed based on the mixed-strategy payoff matrices presented in Table 1 and Table 2. The expected returns to the government's choice of strong and weak regulation are E_{x1},E_{x2} respectively. The average expected return is $\overline{E_x}$. Therefore:

$$E_{x1} = y(E_G - C_G) + (1-y)(E_G + P - C_G) \quad (1)$$
$$E_{x2} = (1-y)[\alpha\beta(P - L_G - R)] \quad (2)$$
$$\overline{E_x} = xE_{x1} + (1-x)E_{x2} \quad (3)$$

The anticipated advantages of agricultural enterprises opting to disclose accurate information and disseminate inaccurate information are denoted as E_{y1},E_{y2}. The average expected return is $\overline{E_y}$. Therefore:

$$E_{y1} = x(E_C + \alpha H_C - C_T) + (1-x)(E_C + \alpha H_C - C_T) \quad (4)$$
$$E_{y2} = x(E_C - C_F - P) + (1-x)[E_C - C_F - \alpha\beta(P + L_C)] \quad (5)$$
$$\overline{E_y} = yE_{y1} + (1-y)E_{y2} \quad (6)$$

According to the Malthusian dynamics equation, the expected return E_x is equal to the expectation E_{x1} minus the average expectation $\overline{E_x}$ (Sun et al., 2021). The resulting equation for the replication dynamics of the government is given as:

$$F(x) = x(1-x)[(1-y)(P + \alpha\beta L_G - \alpha\beta P + \alpha\beta R) + (E_G - C_G)] \quad (7)$$

The equation for the replication dynamics of agribusiness is:

$$F(y) = y(1-y)[x(P-\alpha\beta L_C-\alpha\beta P)-(C_T-C_F-\alpha H_C-\alpha\beta L_C-\alpha\beta P)] \quad (8)$$

When the two sides of the game replicate the dynamic equation to achieve a value of zero when the game is terminated, the players strategy to achieve the optimal solution, the government and agribusiness of the development of the stability of the strategy is analyzed as follows:

As for government, according to Eq.(7), when $dx\ /\ dt = 0$, the stabilizing solution can be obtained as:$x_1 = 0,\ x_2 = 1,\ y^* = (E_G + P - C_G + \alpha\beta L_G - \alpha\beta P + \alpha\beta R)/(P + \alpha\beta L_G - \alpha\beta P + \alpha\beta R)$. The conditions that still need to be met to reach the evolutionary stabilization point are $F'(x) < 0$. Thus, a partial derivation of x gives:

$$F'(x) = (1-2x)[(1-y)(P+\alpha\beta L_G-\alpha\beta P+\alpha\beta R)+(E_G-C_G)] \quad (9)$$

An equilibrium point analysis based on the replication dynamics equation yields: When $y = y^*$,$F(x) = 0$, a stabilization point can be any number of x, The outcomes of the government's choice of strong and weak regulation are the same. When $y > y^*$, $F'(x_1 = 0) < 0$,$F'(x_2 = 1) > 0$. $x_1 = 0$ is a stable equilibrium point. Currently, weak regulation is the government's evolutionary equilibrium strategy. When $y < y^*$, $F'(x_1 = 1) < 0$, $F'(x_2 = 0) > 0$. $x_1 = 1$ is a stable equilibrium point. At this point, strong regulation is an evolutionary equilibrium strategy. As for agribusiness, according to Eq. (8), when $dy\ /\ dt = 0$,the stabilizing solution can be obtained as: $y_1 = 0, y_2 = 1, x^* = (C_T - C_F - \alpha H_C - \alpha\beta L_C - \alpha\beta P)/(P - \alpha\beta L_G - \alpha\beta P)$. The conditions that still need to be met to reach the evolutionary stabilization point are $F'(y) < 0$. Thus, a partial derivation of y gives:

$$F'(y) = (1-2y)[x(P-\alpha\beta L_C-\alpha\beta P)-C_T+C_F+\alpha H_C+\alpha\beta(L_C+P)] \quad (10)$$

An equilibrium point analysis based on the replication dynamics equation yields: When $x = x^*$,$F(y) = 0$, any value of y is a stabilization point. Agribusinesses' choice of strategies for sharing true information versus sharing false information results in the same outcome. When $x > x^*$, $F'(y_1 = 0) > 0$,$F'(y_2 = 1) < 0$. $y_2 = 1$ is a stable equilibrium point. At this point, sharing true information is an equilibrium strategy for agribusiness. When $x < x^*$, $F'(y_1 = 0) < 0$, $F'(y_2 = 1) > 0$. $y_1 = 0$ is the stable equilibrium point. Sharing false information is an equilibrium strategy for agribusiness currently.

3.3 Evolutionary equilibrium stability analysis

The Jacobi matrix is obtained by taking partial derivatives from Eq. (9) and Eq. (10):

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \quad (11)$$

According to Eq. (1)-(10), There are five equilibria in the gaming system: O(0,0); A(1,0); B(0,1); C(1,1); D(x^*, y^*). The equilibrium of this replicated dynamic equation is an evolutionarily stable strategy (ESS) only if the two conditions $trJ < 0$ and $detJ > 0$ are satisfied simultaneously.

This study aims to analyze the influence of each parameter on an evolutionary stabilizing approach. To this end, the model is discussed in four different situations. To simplify the expression, let: $\theta_1 = P + \alpha\beta L_G - \alpha\beta P + \alpha\beta R$,$\theta_2 = P - \alpha\beta L_C - \alpha\beta P$,$\theta_3 = E_G - C_G + P + \alpha\beta L_G - \alpha\beta P + \alpha\beta R$,$\theta_4 = C_T - C_F - \alpha H_C - \alpha\beta L_C - \alpha\beta P$.

Situation 1:$\theta_1 > \theta_3$and $\theta_2 > \theta_4$, the stability analysis results for the game system's five evolved balance points are shown in Table 3, currently, there is no ESS in the system evolution.

Table 3
Equilibrium stability analysis results for $\theta_1 > \theta_3$and $\theta_2 > \theta_4$

Equilibrium point	$detJ$	Notation	trJ	Notation	Outcome
(0,0)	$-\theta_3\theta_4$	–	$\theta_3 - \theta_4$	Unknown	Unstable
(1,0)	$\theta_3(\theta_4 - \theta_2)$	–	$\theta_2 - \theta_4 - \theta_3$	Unknown	Unstable
(0,1)	$\theta_4(\theta_3 - \theta_1)$	–	$\theta_3 - \theta_1 + \theta_4$	Unknown	Unstable
(1,1)	$(\theta_1 - \theta_3)(\theta_4 - \theta_2)$	–	$\theta_1 - \theta_3 + \theta_4 - \theta_2$	Unknown	Unstable
(x^*,y^*)	0	0	0	0	Saddle point

Situation 2: $\theta_1 > \theta_3$and $\theta_2 < \theta_4$, the stability analysis results for the game system's five evolved balance points are shown in Table 4, the system reaches ESS at (1,0).

Table 4
Equilibrium stability analysis results for $\theta_1 > \theta_3$ and $\theta_2 < \theta_4$

Equilibrium point	$detJ$	Notation	trJ	Notation	Outcome
(0,0)	$-\theta_3\theta_4$	−	$\theta_3 - \theta_4$	Unknown	Unstable
(1,0)	$\theta_3(\theta_4 - \theta_2)$	+	$\theta_2 - \theta_4 - \theta_3$	−	ESS
(0,1)	$\theta_4(\theta_3 - \theta_1)$	−	$\theta_3 - \theta_1 + \theta_4$	Unknown	Unstable
(1,1)	$(\theta_1 - \theta_3)(\theta_4 - \theta_2)$	+	$\theta_1 - \theta_3 + \theta_4 - \theta_2$	+	Unstable
(x^*,y^*)	0	0	0	0	Saddle point

Situation 3: $\theta_1 < \theta_3$ and $\theta_2 > \theta_4$, the stability analysis results for the game system's five evolved balance points are shown in Table 5, the system reaches ESS at (1,1).

Table 5
Equilibrium stability analysis results for $\theta_1 < \theta_3$ and $\theta_2 > \theta_4$

Equilibrium point	$detJ$	Notation	trJ	Notation	Outcome
(0,0)	$-\theta_3\theta_4$	−	$\theta_3 - \theta_4$	Unknown	Unstable
(1,0)	$\theta_3(\theta_4 - \theta_2)$	−	$\theta_2 - \theta_4 - \theta_3$	Unknown	Unstable
(0,1)	$\theta_4(\theta_3 - \theta_1)$	+	$\theta_3 - \theta_1 + \theta_4$	+	Unstable
(1,1)	$(\theta_1 - \theta_3)(\theta_4 - \theta_2)$	+	$\theta_1 - \theta_3 + \theta_4 - \theta_2$	−	ESS
(x^*,y^*)	0	0	0	0	Saddle point

Situation 4: $\theta_1 < \theta_3$ and $\theta_2 < \theta_4$, the stability analysis results for the game system's five evolved balance points are shown in Table 6, the system reaches ESS at (1,0).

Table 6
Equilibrium stability analysis results for $\theta_1 < \theta_3$ and $\theta_2 < \theta_4$

Equilibrium point	$detJ$	Notation	trJ	Notation	Outcome
(0,0)	$-\theta_3\theta_4$	−	$\theta_3 - \theta_4$	Unknown	Unstable
(1,0)	$\theta_3(\theta_4 - \theta_2)$	+	$\theta_2 - \theta_4 - \theta_3$	−	ESS
(0,1)	$\theta_4(\theta_3 - \theta_1)$	+	$\theta_3 - \theta_1 + \theta_4$	+	Unstable
(1,1)	$(\theta_1 - \theta_3)(\theta_4 - \theta_2)$	−	$\theta_1 - \theta_3 + \theta_4 - \theta_2$	Unknown	Unstable
(x^*,y^*)	0	0	0	0	Saddle point

A comprehensive analysis of the above 4 situations can be derived:

(1) When the condition $\theta_2 < \theta_4$ holds, the game system eventually converges to the point (1,0) over time, at which point agricultural firms adopt a negative attitude towards sharing false information. Since the speculative gains that agricultural enterprises obtain by reducing the cost of information sharing are significantly higher than the government fines, they need to bear, and the speculative gains far exceed the brand reputation gains. In this case, agribusinesses always tend to choose to share false information.

(2) When the conditions $\theta_1 < \theta_3$ and $\theta_2 > \theta_4$ hold at the same time, the game system eventually converges to the point (1,1) over time. At this time, although the government will pay more costs for choosing strong regulation, the benefits thus obtained can not only cover the overpaid regulatory costs, but also bring the government benefits such as social prestige, so the government is more inclined to choose the strong regulation strategy.

In summary, under certain conditions, the game system may eventually converge to the point (1,0) or (1,1) over time, and the evolutionary trend is closely related to the magnitude of the values of the parameters such as gain, loss, and probability (1,0).

4. Numerical Simulation Analysis

In order to verify the accuracy of the above derived analysis, the study will set the simulation parameters on the basis of meeting the basic requirements of parameter values, and numerical simulation is done with MATLABR2016b. The simulation parameters are set as shown in Table 7.

Table 7
Simulation parameter settings

E_G	C_G	E_C	H_C	C_T	C_F	P	α	β	R	L_C	L_G
10	8	20	4	16	10	6	0.5	0.4	2	10	5

By analyzing the game system, A close correlation is observed between the evolutionary trajectory and certain magnitudes of the values of parameters such as gain, loss, and probability. To validate the aforementioned derivation, the evolutionary impacts of the parameter value sizes on the gaming system will be analyzed in terms of four parameters, the probability of consumers choosing to pay attention to the traceability information (α), the probability of media accurately reporting the information (β), the government's punishment for the false behavior of the enterprise (P), and the enterprise obtaining the gain of the brand reputation (H_C), respectively.

4.1 Numerical analysis of the probability of consumers choosing to focus on traceability information (α)

The attention of consumers to traceability information directly affects the motivation of enterprises to share information on the blockchain. In order to investigate the influence of the probability α of consumers' attention to traceability information on the evolution results of the game system, α is taken to be the values of 0, 0.2, 0.4, 0.6, 0.8, and 1. The values of the rest of the parameters are unchanged as shown in Table 7. Fig. 1 shows the simulation outcomes. From Fig. 1, when α is equal to 0, there is no evolutionary stabilization strategy for the system. In the case where consumers are not interested in the traceability information, firms still face the risk of potential negative impacts caused by media exposure. Such media exposure can lead to the erosion of public trust in a company, which can be detrimental to the company's reputation and brand value. Consequently, companies may be inclined to upload false information on the blockchain for cost-saving reasons to avoid possible negative consequences. Enterprises may reduce the probability of sharing true information, and at the same time contribute to the government's tendency to adopt stricter regulatory strategies. Firms are primarily driven by the objective of maximizing short-term profits, whereas governments are primarily concerned with ensuring fairness and transparency in the market. The divergence of these two sets of objectives makes it challenging for the system to reach an evolutionary stable state.

As the α value gradually increases from 0.2 to 1, the system emerges over time with a desirable evolutionary stabilization strategy: the government chooses to strongly regulate, and the agricultural product enterprises choose to share true information. While the probability of agribusinesses choosing to upload truthful information on the blockchain gradually decreases in the initial stages of evolution, as consumer concerns about food safety and product traceability increase, the government receives calls from the public and stakeholders for stronger regulation of food safety and business practices. Under such circumstances, the government would be more inclined to adopt strong regulatory measures in response to public concerns and to safeguard the image and reputation of the government. With the increasing probability of strong government regulatory strategies, agribusinesses are also forced to gradually increase the probability of uploading true information on the blockchain, so the system moves towards an evolutionary steady state where sharing true information and strong regulation coexist.

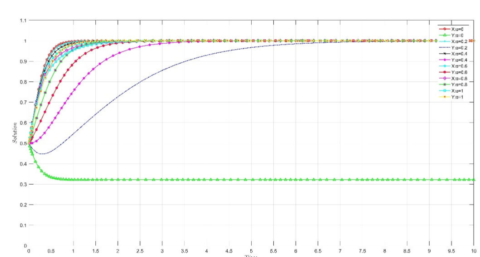

Fig. 1. Dynamic evolution involving varying values of α

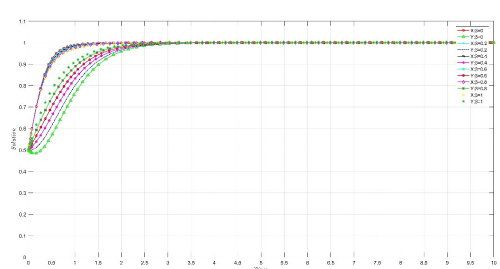

Fig. 2. Dynamic evolution involving varying values of β

4.2 Numerical analysis of the probability of accurate media coverage (β)

Incorrect or incomplete information reported by the media may mislead consumers to make wrong purchasing decisions and indirectly affect the incentives of enterprises to share information on the blockchain. To investigate the influence of the probability of accurate media reporting on the event on the evolution results of the system, let β=0,0.2,0.4,0.6,0.8,1 and keep other parameters unchanged, the simulation results obtained are shown in Fig. 2. From Fig. 2, we know that when β takes the value of 0, the system can appear the ideal evolutionary stability point, and the government implements strong regulation and promotes the sharing of real information among enterprises. At this time, the behavioral choices of agricultural enterprises were greatly influenced by the government, and their tendency to upload real information in the blockchain showed a dynamic process of first decline and then increase. This trend reflects the fact that enterprises gradually recognize the positive effects of uploading real information in the blockchain on the long-term development of the enterprise after a period of resistance and adaptation to the change in the early stages of the policy, and therefore adjust their strategies. As the β value gradually increases from 0 to 1, media reporting accuracy has a reverse effect on government behavioral choices, but its effect is not significant. This suggests that the government is more influenced by other factors, such as the tendency of policy makers and pressure from stakeholders, rather than simply by the accuracy of media reports. In contrast, there is a positive effect on firms' behavioral choices, implying that firms are more inclined to upload truthful information on the blockchain in environments where the accuracy of media reports is higher. As the value of β increases, more accurate media reports provide a clearer information base, which accelerates the adjustment of corporate strategies and the convergence of the system.

4.3 Numerical analysis of the penalty (P)

In addition to third-party regulation, the government's regulatory measures not only directly affect the behavioral choices of enterprises, but also indirectly affect the responses of consumers and media. In order to further analyze the evolutionary impact of the government's regulatory actions on the game system, other parameters are kept constant, and the corresponding values of P are established as 0, 2, 4, 6, 8, and 10. the simulation results are shown in Fig. 3.

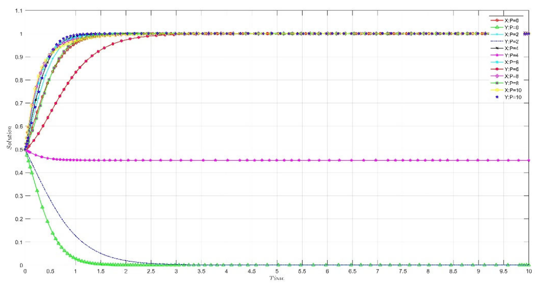

Fig. 3. Dynamic evolution involving varying values of P

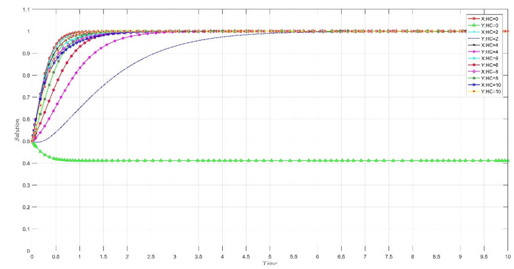

Fig. 4. Dynamic evolution involving varying values of H_C

From Fig. 3, we know that when P gradually decreases from the initial value of 2, the system appears to evolve a stable strategy. As the number of penalty decreases, the fines imposed by the government is gradually weakened, and enterprises face lower fines even if they are found to have violated the law, and choosing to upload false information in the blockchain is less costly for enterprises. Thus, the rate of evolution accelerates on both sides, favoring the (strong regulation, sharing false information) strategy as the optimal decision combination. With an initial value of 4, the system does not have an evolutionary stabilization strategy. At this point, the fine amount is in the interval where companies are neither willing to take the risk of violating the law nor pay more sharing costs, resulting in the system failing to reach a stable state. As the value of P takes on a gradual increase from 6, the evolutionary trend of the government and agricultural enterprises shifts to (strong regulation, sharing true information), indicating that when the fine amount is large, the increase in the fine amount makes the enterprises feel more pressure and risk, and thus they are more inclined to comply with the rules to upload real information in the blockchain. Therefore, by increasing the amount of penalty that firms must bear for violating the rules, it can significantly accelerate the rate of convergence of the government and agribusinesses towards the outcome of (strong regulation, sharing true information).

4.4 Numerical analysis of the brand earnings(H_C)

The above analysis has clearly elucidated the impact of the monitoring behavior on the entire system evolution, Inquire further into the effects of brand gain obtained by the enterprise on the overall system evolution process and change the value of the brand gain H_C, take the value of 0, 2, 4, 6, 8, 10. the rest of the parameters remain unchanged. The simulation results are shown in Fig.4. From Fig. 4, we know that when H_C takes the value of 0, there is no evolutionary stable strategy in the system. In the case of not being able to obtain any positive benefits such as brand reputation, enterprises are more inclined to adopt a conservative strategy rather than actively sharing true information. As the probability of agricultural enterprises choosing to upload true information in the blockchain decreases, it leads to a tendency for the government to choose strong regulation. However, in the current environment, businesses are finding that sharing truthful information does not bring immediate benefits or rewards. On the contrary, if enterprises disclose true information on the blockchain, they may face risks such as information leakage and loss of competitive advantage, and the uncertainty associated with these risks may cause enterprises to choose negative behaviors. Therefore, although the government tends to adopt a strong regulatory strategy to ensure product quality and market order, it is not sufficient to solve the problem of enterprises' reluctance to upload real information on the blockchain. As the value of H_C takes a gradual increase from 2, the system appears to have a desirable evolutionary stable strategy over time: the government chooses to strongly regulate, and enterprises choose to share real information. Firms realize that they can gain consumers' trust and loyalty by uploading truthful information on the blockchain, which directly contributes to the evolution of their strategies towards uploading truthful information on the blockchain. Firms' pursuit of branding gains changes market dynamics and influences the government's strategic choices. The government realizes that as firms increasingly tend to share authentic information, a gradual decrease in regulatory intensity can also maintain market order and product quality. As a result, the government gradually reduces the rate at which its strong regulatory strategy reaches evolutionary stability, supports firms' self-regulatory behavior, and maintains the stability and health of the market. This interaction drives the system toward an evolutionary stable state where sharing truthful information and strong regulation coexist.

5. Conclusions and recommendations

5.1. Conclusions

Blockchain technology is an effective tool for solving the problems of information asymmetry and low member trust in traditional traceability systems. However, blockchain can ensure the immutability of uploaded data, but it cannot guarantee the authenticity of initial information uploaded by participants. To better identify the factors affecting their compliance with the rules for uploading authentic information, this research investigates how decisions are made by every individual involved in the agricultural product traceability system through the evolutionary game method, focusing on the factors affecting the decision-making of the participants, especially those related to their revenue mechanisms, penalties, and monitoring behaviors. Through in-depth study of these factors, targeted suggestions and solutions can strengthen the infrastructure for tracing agricultural products. The following are the primary findings of this work:

(1) The government has stimulated positive corporate behavior through incentives and penalties, an approach that not only helps the government to ensure product quality and safety, but also helps companies to build trust and a good brand reputation, maximizing the long-term benefits for both parties. (2) Consumers and the media play a crucial role in improving traceability systems for agricultural products. They can act as a third-party force to monitor when government regulation fails, thereby boosting the agriculture supply chain's accountability and ability to be tracked. (3) Businesses are usually profit-oriented, so consumer attention to produce traceability information does not directly motivate businesses to choose to share authentic information. It is only when consumer attention leads to benefits for the brand that firms are directly motivated to choose the behavior of sharing authentic information. (4) The government can be somewhat lax in the process of regulating the traceability of agricultural products due to media scrutiny. However, given the inauthenticity of media reports, the government still needs to continue to play a monitoring role to guarantee traceability as well as security of the agricultural supply chain.

5.2 Recommendations

Based on the above conclusions, to further improve and refine the government's management of the traceability system for agricultural products to ensure public safety and rights. The following are some targeted recommendations:(1) The government must adjust the level of penalties to align with the actual situation. The number of penalties should be sufficiently severe to ensure that enterprises comply with the rules, while also ensuring that it does not constitute an excessive burden on their survival and development. Through continuous monitoring and evaluation, the effectiveness of the penalty mechanism should be ensured to maximize enterprises' compliance with traceability requirements. (2) Government departments should establish a perfect internal supervision mechanism to ensure that the government is not affected by media supervision and slackness in the process of traceability supervision of agricultural products. At the same time, communication and coordination with the media should be strengthened to respond to and explain relevant reports in a timely manner, to maintain the stability of the government's image and regulatory efforts. (3) The government can encourage consumers and the media to actively participate in the supervision of the traceability system for agricultural products by setting up specialized complaint and reporting channels. In addition, consumers should not just passively accept the enforcement of government regulators but should consciously take on the responsibility of third-party supervision and increase their awareness and participation as the main beneficiary group of agricultural product traceability information supervision. When purchasing agricultural products, they should consciously choose those brand products with positive behavior.

The study delves into the behaviors and decisions of the parties in the agricultural product traceability system, as well as the interactions among them. Through the establishment of an evolutionary game model, it is found that in the agricultural product traceability system, the government incentive and penalty policies, the supervision of consumers and the media, and the profit drive of enterprises jointly drive the system towards the ideal state, which means that strong supervision and sharing of true information are chosen as the optimal strategy. However, this study also has some limitations: (1) In order to simplify the analysis, only a limited number of significant and well-known influencing factors are considered. The parameter settings in this paper are based on previous research, and whether they are instructive for the real situation still needs to be examined. Future research can extend the consideration of influencing factors, such as policy environment, market competition pattern, etc. And empirical studies can be used to validate and supplement the conclusions of the model, to enhance the credibility and applicability of the study. (2) The role of consumers and the media in producing traceability systems is profound. They may be disseminators of information, monitors, or even decision makers. Therefore, considering them only as influencing factors may not provide a full understanding of their role in the system. Future research can construct a tripartite evolutionary game model of the government and agricultural enterprises with the participation of a third-party monitoring force, which can more accurately explore the interactions and influences between the parties in real situations.

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