Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 August 2025
DOI 10.3389/fsufs.2025.1637246

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RECEIVED 29 May 2025
ACCEPTED 23 July 2025
PUBLISHED 12 August 2025

CITATION
Zhang J, Cao Z and Qu X (2025) Research on the influencing mechanism of enterprises' adoption intention toward blockchain-based food safety traceability systems: a UTAUT model perspective.
Front. Sustain. Food Syst. 9:1637246.
doi: 10.3389/fsufs.2025.1637246

Research on the influencing mechanism of enterprises' adoption intention toward blockchain-based food safety traceability systems: a UTAUT model perspective

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Amid growing public concerns over food safety, blockchain-based traceability systems have emerged as a transformative solution. However, their widespread implementation critically depends on organizational adoption willingness. This study bridges a significant research gap by investigating the multidimensional drivers of adoption behavior through an extended Unified Theory of Acceptance and Use of Technology (UTAUT) model, incorporating enterprise-specific variables—informational motivation, perceived risk, perceived cost, and system compatibility. Employing qualitative comparative analysis (QCA) on rigorously validated survey data from 603 food enterprises, we identify five distinct high-adoption pathways. Our findings demonstrate that adoption decisions result from synergistic interactions of multiple factors rather than isolated conditions, revealing three dominant adoption logics: (1) external pressure-driven, (2) internal value-driven, and (3) contradiction-balancing. The study makes dual contributions: theoretically, it advances technology adoption literature by developing a context-specific framework; practically, it offers actionable insights for promoting blockchain implementation—including multifactor synergy optimization, targeted intervention strategies for heterogeneous enterprises, risk-cost expectation management, and compatibility enhancement to reduce adoption barriers.

KEYWORDS

blockchain, food safety traceability system, enterprise adoption intention, UTAUT, QCA

1 Introduction

China's '14th Five-Year Plan for National Food Safety' (2021–2025) implements the 'Healthy China 2030' initiative and Food Safety Law. This policy explicitly advocates applying blockchain technology to enhance intelligent food safety supervision. This plan clearly proposes to strengthen the construction of intelligent supervision capacity and promote the application of new technologies such as blockchain in the field of food safety traceability; The General Office of the State Council is an institution that assists the leading comrades of the State Council in dealing with the daily work of the State Council. It bears important responsibilities such as comprehensive coordination, service guarantee, and supervision and implementation. The "Opinions of the General Office of the State Council on Accelerating the Construction of an Important Product Traceability System" issued by the General Office of the State Council requires the food industry to build a full-chain traceability mechanism with "traceable sources, traceable destinations, and accountability"; the "Implementation Opinions on Promoting the Quality and Safety Traceability of Key Industrial Products" issued by the General Administration of Market Supervision has listed blockchain technology as the core support technology for food quality and safety traceability. The research indicates that when policies list blockchain as the core supporting technology for food quality and safety traceability, enterprises, driven by both compliance requirements and the construction of market trust, will prioritize blockchain traceability systems as the primary choice for optimizing supply chain management (Tanwar et al., 2022). This clearly shows that the mandatory requirements of policies and regulations and the standardized guidance of industry standards It has become the primary driving force for enterprises to deploy blockchain traceability systems (Gupta and Shankar, 2024).

However, promoting China's food safety traceability system faces a key challenge: guiding enterprises to adopt it proactively. Despite policy support, enterprises encounter barriers in technology, cost, and management during adoption. From international studies that SMEs in developing countries generally face problems such as weak infrastructure and lack of resources when implementing food safety traceability systems (Lee et al., 2023); and the high cost of blockchain hardware equipment, data storage, and manpower, as well as the weak informatization foundation of SMEs further raise the threshold of technological application (Dzwolak, 2016); and also have study showed that although expanding markets and meeting regulatory requirements are the core motivations for enterprises to adopt related technologies, high costs and differences in enterprise size constitute the main implementation barriers (Barbancho-Maya and López-Toro, 2022). Meanwhile, some researchers reveal enterprises are confronted with multiple constraints such as technology, cost and management, and existing research lacks a systematic analysis of the synergy effects of multi-dimensional factors such as performance expectations, community influence and perceived risks, as well as the psychological mechanism of enterprise technology adoption (Luo et al., 2022). Others point out that the management of normative stakeholders can significantly enhance the willingness and behavior of supply chain members to adopt the blockchain food safety traceability system (Kramer et al., 2021; Anastasiadis et al., 2025). Additionally, a group of scholars emphasizes that although the blockchain enabled food safety traceability system is regarded as a key technology for enhancing the transparency of the supply chain, enterprises' willingness to adopt it is restricted by factors such as insufficient maturity of technology implementation, ambiguous cost–benefit assessment, lack of standardization and interoperability, limited practical application cases, and insufficient quantitative assessment of sustainability (Dasaklis et al., 2022; Jaison and Ramaiah, 2022). Although existing studies have explored the influencing factors of enterprise adoption of food safety traceability system, there are still deficiencies: first, most of the studies focus on a single level of influencing factors, but there is a lack of systematic analysis of the synergistic effect and group logic of multi-dimensional factors, such as performance expectations, social influence, and perceived risk, which makes it difficult to reveal the intrinsic mechanism of enterprise adoption decision-making in complex management situations (Zhou and Xu, 2022). Second, although the existing studies mention that regulatory requirements and market expansion are the core motives, they lack in-depth explanations of the psychological mechanisms of technology adoption, such as value cognition driven by informational motives, and the inhibitory effect of perceived risk on decision-making.

In view of the above research gaps, the choice of the UTAUT model as the theoretical framework in this paper is remarkably reasonable: the UTAUT model integrates four core variables, namely, performance expectation, effort expectation, social influence, and contributing factors, which can systematically depict the driving mechanism affecting the adoption intention of enterprises, Building on UTAUT, we introduce enterprise-level variables (informational motivation, perceived risk, cost, compatibility) to address the model's original oversight of organization-specific factors, which make the theoretical framework closer to the complex decision-making situation of enterprise adoption (Pappa et al., 2018). Moreover, the multidimensional variable structure of the model provides a suitable analytical foundation for the subsequent use of the fsQCA method, which breaks through the linear assumption of the traditional regression analysis and reveals the multiple concurrent causal relationships by taking the factors of performance expectation and social influence as conditional variables and identifying the group effects of the different combinations of conditions on the willingness to adopt.

This study not only helps to deeply analyze the psychology and behavioral patterns of enterprises in the face of emerging technologies, but also provides theoretical support and practical guidance for the promotion and application of blockchain food safety traceability system. By accurately grasping the needs and preferences of enterprises and optimizing the system design and service experience of, it is expected to promote the more efficient integration of blockchain technology into the food safety supervision system, and effectively guarantee the safety of people's "tongue".

2 Theoretical model

The willingness of enterprises to adopt blockchain-based food safety traceability systems represents a complex decision-making process that demands holistic investigation and interpretation through multiple theoretical lenses. As a classic framework in information technology adoption research, the UTAUT model integrates core theoretical elements—such as the Task-Technology Fit model and innovation diffusion theory—with its core dimensions (performance expectations, effort expectations, social influence, and contributing factors) providing a theoretical anchor for identifying key drivers of enterprise adoption behavior (Lin and Wu, 2021).

As the focal agents in food safety assurance, enterprise adoption behavior directly impacts the effectiveness of food safety traceability systems, whose internal influence mechanisms cannot be fully deconstructed through a single theoretical perspective. Building upon UTAUT, this study introduces enterprise-level variables—informational motivation, perceived risk, perceived cost, and compatibility—to form a multidimensional analytical framework. These factors do not act in isolation; instead, they shape adoption decisions through complex interactions: between performance expectations and value-driven informational motivation, between effort expectations and compatibility-related implementation resistance, and between social influence and the external push from facilitating conditions. Only by analyzing the interactive logic of these influencing factors across multi-theoretical perspectives can we grasp the intrinsic motivations behind enterprise adoption and provide theoretical support for blockchain applications in food safety. The research model is illustrated in Figure 1.

3 Factor identification

3.1 Performance expectations

The core of a Blockchain-Based Food Safety Traceability Systems is to build and satisfy the market's expectation of the system's performance, which is directly related to the enterprise's strategic goals of improving service quality, enhancing market competitiveness and realizing sustainable development. As a key indicator for measuring the success of the system, performance expectation not only reflects the market's expectation of the actual performance and results of the system, but also constitutes an important driving factor for enterprises to adopt and optimize the system.

When deploying the system, enterprises expect to realize the improvement of food safety management efficiency and accuracy through blockchain technology. The system's operation mechanism is manifested in the accurate recording of information on all aspects of food from source to terminal and real-time synchronization to the blockchain, forming a whole-chain information traceability system (Wang et al., 2020). This traceability provides enterprises with a food safety risk prevention and control tool, which reduces the risk of food safety accidents while having an impact on the protection of consumer health rights and interests and the improvement of public confidence in food safety. The transparency of the production process brought about by blockchain technology enables enterprises to show the outside world information about the source, processing and distribution of products, which in turn affects consumers' trust in product-related links (Hao et al., 2020). The accumulation of trust is associated with corporate image building, brand reputation enhancement and market competitiveness enhancement, and may play a role in customer retention, new market development and market position consolidation (Panghal et al., 2024). In the evaluation and decision-making process, enterprises will combine their own development needs and market expectations to analyze the system's role in optimizing food safety management processes, improving operational efficiency and reducing operational costs, and pay attention to the system's performance in streamlining the traceability process, responding to food safety crises, and optimizing the consumer shopping experience. Through the evaluation, enterprises can identify the long-term value and potential benefits of the system, which in turn influences their adoption decisions and technology application strategies.

3.2 Effort expectations

In the field of food safety, effort expectation constitutes a key dimension in measuring the effort and professionalism required for enterprises to embrace a Blockchain-Based Food Safety Traceability Systems. Blockchain technology, with its decentralization, high transparency, and data immutability, has the potential to be applied in improving food safety management, but its technical threshold and professional complexity may be an obstacle to adoption by enterprises.

The integrity of the technical support system is also an important factor affecting the expectation of effort. When users encounter technical problems or functional doubts in the use of the system, timely access to professional support can reduce their application barriers. The support content covers technical problem solving, system function analysis and operation skill explanation, etc. to help users understand and utilize the system more effectively.

3.3 Social influence

In the field of food safety, the role of social influence as a social factor in the acceptance of blockchain technology-based food safety traceability system by enterprises is closely related to the social network in which enterprise users are located. This network includes key players such as partners, employee groups, food industry experts,

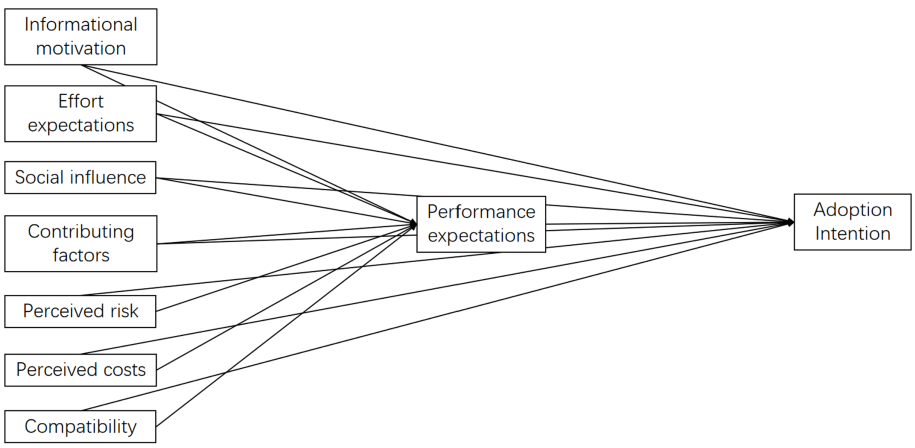

FIGURE 1
Research mode.

and opinion leaders, whose perspectives, experiences, and feedback collectively form a complex network of relationships that influence corporate awareness and adoption decisions.

Social influence acts on the system acceptance process through a two-way mechanism. After adopting blockchain technology to build a food safety traceability system, advanced enterprises in the industry have improved their management efficiency, risk control effectiveness and enhanced consumer trust, which form a demonstration effect through word-of-mouth and case sharing, and constitute a positive driving factor influencing the decision-making of other enterprises. At the same time, the professional evaluation of authoritative organizations and the recognition of industry opinion leaders increase the trust endorsement for the system, which becomes an important reference basis for influencing adoption decisions. On the other hand, negative feedback in the community may have an inhibitory effect on enterprise acceptance behavior. Skeptical views, bad experience or negative practice cases in the industry are easily spread and amplified in the sensitive context of food safety, which may cause enterprises to have doubts about the effectiveness of the system, and even trigger overall concerns about the applicability of blockchain technology in the field, thus affecting the advancement of the adoption decision.

3.4 Contributing factors

In the food safety management framework, contributing factors constitute the core drivers for enterprises to adopt a Blockchain-Based Food Safety Traceability Systems. These factors cover the dimensions of organizational support, technological maturity and social environment, forming a composite driving system that influences the adoption decision of enterprises.

System availability is a fundamental consideration in enterprise adoption decisions. The stability and reliability of a blockchain traceability system that has the ability to dock information from the whole chain (production, processing, circulation, etc.) affects the accuracy of food safety supervision by enterprises. By realizing continuous recording and efficient processing of food information, the system plays a role in the efficiency of enterprise management process, which in turn affects the degree of trust of enterprises in the system. The perfection of technical support system is the key condition for enterprises to apply the system continuously. The system includes professional training, technical consulting and customized solutions, aiming at lowering the technical operation threshold of enterprise users and promoting the full play of system functions. There is a correlation between the effectiveness of technical support and the learning cost of enterprises and the efficiency of system implementation. The policy and regulatory environment, as an external influencing factor, provides institutional support for enterprises by clarifying the normative framework for food safety and blockchain technology applications. Targeted policies not only establish system operation standards, but also have an impact on the industry's mutual trust mechanism and cooperation mode, constituting an important external reference for enterprise decision-making. Social infrastructure support is a necessary condition for system operation, including network coverage and data security measures. Extensive network infrastructure ensures the real-time transmission and sharing of food information, while data security mechanisms involve the protection of business information and user privacy, both of which jointly affect the operational efficiency of the system and the perception of enterprise data security.

When the above contributing factors reach certain conditions, the resistance of enterprises to adopt the system may be reduced. These factors act on the decision-making process of enterprises through different paths, forming an interactive relationship between the application of technology and management needs, and constituting a realistic basis for the popularization of the food safety traceability system.

3.5 Informational motivation

In the field of food safety, informational motivation serves as the core driving force for enterprises to adopt blockchain traceability systems. Its theoretical foundation can be traced back to Kuhlthau's information-seeking theory, emphasizing that organizations can reduce environmental uncertainty and enhance decision-making efficiency by proactively obtaining information (Kuhlthau, 1991). This motivation is in line with the "performance expectation" dimension of the UTAUT model, but it focuses more on the data-driven decision-making needs at the organizational level. The data processing capability of the blockchain traceability system can achieve real-time updates and accuracy guarantees of food safety traceability information, enabling enterprises to access the system and obtain real-time data throughout the entire chain (Yakubu et al., 2022).

The immediacy and accuracy of the information in the system meets the requirements of enterprises for timeliness and reliability of data, and supports their monitoring and tracing of various links in the food supply chain. This full-chain traceability allows companies to keep track of food safety and address potential risks. Enterprises see the system as a tool to enhance their competitiveness in the marketplace, and believe that the system can show consumers the transparency of the production and distribution chain, which in turn influences consumer trust and brand loyalty (Stranieri et al., 2017). At the same time, the system's data can be used for market analysis and supply chain optimization, contributing to operational efficiency. With the popularization of the system, an information sharing and cooperation mechanism is formed among enterprises, which is related to their trust and dependence on the system. The popularization of the system also involves information interaction among government, enterprises, and consumers, which constitutes one of the influencing factors of the food safety regulatory environment. Informational motivation becomes an important logical chain driving the adoption behavior of enterprises by connecting their management needs with the functional characteristics of the system.

3.6 Perceived risk

The perceived risks of enterprises to the blockchain traceability system are based on the consumer risk theory proposed by Bauer, which defines risk as "the uncertainty of decision-making results". However, this study extends it to the organizational level, focusing on enterprise-specific risk dimensions such as data security and compliance pressure. This risk perception is associated with the degree of users' trust in the accuracy and efficiency of the system in performing food safety traceability tasks and the ability to guarantee consumers' health and safety.

System applications face multiple risks associated with virtual network environments, including information asymmetry, cybersecurity threats and cyberprivacy protection issues. Information asymmetry manifests itself as a cognitive barrier in users' understanding of the system's operation mechanism, data accuracy, and security performance, which may lead to concerns about the reliability of the system. Network security risks cover potential threats such as data leakage, tampering or unauthorized access, which may lead to distortion of food traceability information or leakage of users' personal information, affecting the security of the system application (van Hilten et al., 2020; Iftekhar and Cui, 2021). The issue of network privacy protection is special in the system application. User personal information and consumption habit data, as the basis of the optimized services of the system, may trigger users' concerns about privacy and security if they are not handled properly. Whether the protection mechanism of such sensitive information is perfect or not directly affects users' trust and willingness to adopt the system (Garaus and Treiblmaier, 2021). Perceived risk forms a resistance factor in technology adoption decision-making by affecting users' assessment of system stability and security. Users' concerns about information asymmetry, network security and privacy protection may lead to a cautious attitude or avoidance of the system, thus affecting the social base of technology promotion.

3.7 Perceived costs

In the field of food safety, Zeithaml's perceived cost theory provides a theoretical perspective for enterprises to adopt a Blockchain-Based Food Safety Traceability Systems (Zeithaml, 1988). Especially the "sacrifice dimension" of its theory of perceived cost. When introducing the system, enterprises make a comprehensive assessment of the direct monetary expenditures (purchase, subscription, installation, maintenance, and upgrade costs) versus the total cost inputs of the technology mastery application, and form a decision correlation with the expected benefits. Kloter's Perceived Cost Framework breaks down the cost challenges faced by organizations into four dimensions: Monetary costs, where organizations need to consider the initial investment and long-term operational costs, as well as the impact of these costs on the business and consumers through the supply chain; Time costs, which relate to the resources required for system familiarity, employee training, and internal process optimization; and Energy costs, which focus on the cost of The cost of energy focuses on the consumption of mental and psychological resources during complex data processing, traceability risk analysis and strategy development; the cost of physical strength does not involve high-intensity physical activity, but the processing of large amounts of information and rapid response in emergencies may cause physiological and mental stress to employees. Enterprises will make systematic evaluation based on the above cost dimensions to form the basis for judging the feasibility and economy of the technology in the decision-making process of technology adoption.

3.8 Compatibility

In the realm of food safety management, compatibility, as a key variable, influences the integration effect of the blockchain food safety traceability system with the existing enterprise system. Its theoretical basis stems from the core dimension of Rogers' innovation diffusion theory, namely, "the degree of matching between technology and the organization's existing values, processes, and systems." The compatibility refers to the degree of fit between the system and the enterprise's existing food safety management process, information technology system and organizational food safety culture, covering system docking at the technical level, synergistic matching of management concepts, and the ability to integrate data processes and operational practices. A highly compatible system can be integrated into the enterprise's food safety management system to realize the traceability control of the whole process from raw material procurement to product listing (Lin et al., 2019). A traceability system integrated with the enterprise's existing information system can guarantee the continuity, consistency and completeness of food safety data in the process of collection, transmission and storage, and provide a data basis for risk assessment and problem tracing (Lin et al., 2022). Compatibility becomes an important factor in determining the implementation effect of the food safety traceability system by affecting the adaptability of the system to the management structure of the enterprise. Its core role is reflected in the promotion of management process convergence, data resource integration and organizational culture adaptation, constituting the key dimension of the interaction between technology application and the existing system of the enterprise.

4 Research design

This study was conducted using a questionnaire. The structure of the questionnaire covers three parts, including the basic characteristics of enterprises, the measurement of variables, and the application of enterprise blockchain traceability system. In order to enhance the reliability of the research data, all measurement questions are adaptively adjusted and optimized with reference to the existing research results and in combination with the specific application scenarios of blockchain-based food safety traceability system.

The variable system constructed in this study consists of three categories: explanatory variables, outcome variables and control variables, and the specific measurement is based on the UTAUT theoretical model and its extension framework (Sharma et al., 2023). In order to exclude the interference of the basic characteristics of the enterprise on the willingness to adopt, the control variables are selected as the enterprise size, the number of years of establishment, the nature of the enterprise, and the mode of operation. The core explanatory variables involve eight dimensions: performance expectation, effort expectation, social influence, enabling factors, informational motivation, perceived risk, perceived cost, and compatibility, and the outcome variable is set to be the enterprise's willingness to adopt. All variables were quantitatively measured using a five-point Likert scale (1 = "Strongly Disagree," 5 = "Strongly Agree"), with 3–4 standardized measurement items for each dimension (see Table 1 for details).

TABLE 1 Sample variable measurement question items and reliability statistics.

Variable	Serial number	Subject	CITC	Cronbach's α	Reference source
Performance expectations	PE1	Adopting a blockchain food safety traceability system can significantly improve the operational efficiency of our organization.	0.685	0.856	Venkatesh et al. (2003)
	PE2	Adopting a blockchain food safety traceability system can significantly improve the intelligence and digitization of our business.	0.718		
	PE3	Compared with the traditional way, blockchain food safety traceability system is extremely helpful for this enterprise to improve the efficiency of food safety monitoring.	0.682		
	PE4	Adopting a blockchain food safety traceability system can help our organization control and improve product quality.	0.711		
Effort expectations	EE1	It does not take a lot of time and effort for employees to learn how to use a blockchain food safety traceability system.	0.649	0.795	Dianwei et al. (2024)
	EE2	Employees are able to quickly adapt and become proficient in using the system to perform their daily tasks.	0.637		
	EE3	It is very easy and fast to check food information using the blockchain food safety traceability system.	0.629		
Social influence	SI1	Many of the partners or competitors have already adopted blockchain food safety traceability systems.	0.644	0.793	Dianwei et al. (2024)
	SI2	The use of blockchain food safety traceability system helps this organization to gain a competitive edge in the industry.	0.629		
	SI3	The enterprise will seriously consider introducing the system and start applying it in its own business after observing the successful use of the system by other entities.	0.636		
Contributing factors	CF1	Our enterprise has sufficient resources (e.g., financial and technical support) to implement a blockchain food safety traceability system.	0.664	0.819	
	CF2	Corporate management expressed strong support and commitment to the introduction of a blockchain food safety traceability system.	0.679		
	CF3	There are explanatory materials and guidelines for businesses to access when using blockchain food safety traceability systems.	0.671		
Informational motivation	IM1	Our enterprise can obtain more detailed and accurate food safety traceability information through blockchain technology.	0.691	0.82	
	IM2	The system provides timely and reliable food safety data to help our organization make better decisions.	0.651		
	IM3	This system allows our company to enhance the transparency of each link in the supply chain and reduce information asymmetry.	0.679		
Perceived risk	PR1	The concern is that the information obtained through the blockchain food safety traceability system is not reliable.	0.659	0.816	
	PR2	Concerns that using the system will create additional compliance challenges and regulatory pressures on the organization.	0.682		
	PR3	Concerns that the use of blockchain food safety traceability systems could put businesses at risk of data breaches.	0.665		
Perceived costs	PC1	Understanding and mastering blockchain food safety traceability systems requires more time, effort and money from companies and employees.	0.67	0.794	
	PC2	System maintenance incurs ongoing organizational expenses.	0.637		
	PC3	The value of food safety assurance for businesses using blockchain food safety traceability systems has not outweighed the costs that may be incurred.	0.603		

(Continued)

TABLE 1 (Continued)

Variable	Serial number	Subject	CITC	Cronbach's α	Reference source
Compatibility	CC1	Blockchain food safety traceability system can be well integrated into the existing food safety management system of this enterprise.	0.674		
	CC2	The system is highly compatible with our business processes, information systems and corporate culture.	0.662	0.818	
	CC3	The introduction of this system will not negatively impact the day-to-day operations of the organization, but rather enhance overall efficiency.	0.677		
Adoption Intention	AI1	Interested in blockchain food safety traceability system and intend to go ahead and try to adopt blockchain food safety traceability system.	0.617		
	AI2	Corporate programs will adopt blockchain food safety traceability systems within a certain period of time.	0.672	0.802	
	AI3	Companies have adopted or have formed a resolution to adopt a blockchain food safety traceability system.	0.656		

5 Data sources

5.1 Data collection

In this study, the questionnaire method is used to collect data, the group sample is food enterprises, and the questionnaires are distributed and recovered through online channels. A total of 615 questionnaires were distributed, removing invalid questionnaires, such as filling in with missing items, all the values of the measurement items are the same or most of them are extreme values, etc., and finally 603 valid questionnaires were recovered, with a recovery rate of 98%. The sample distribution is shown in Table 2.

Table 2 shows that 59.20% of the sample are "Micro and Small Enterprises (number of employees<100, revenue<20 million yuan)." In addition, the proportion of medium-sized enterprises (100 employees<300 employees, 20 million yuan≤ business revenue<100 million yuan) is 35.49%. 49.92% of the sample will choose ">3 ~ 10 years." From the perspective of 3. nature of the enterprise, there are relatively more "private enterprises" in the sample, with a proportion of 68.33%. From 4. business mode distribution, most of the samples are "food processing enterprises," the proportion is 46.93%. In addition, the proportion of food production enterprises is 34.66%.

5.2 Reliability and validity tests

5.2.1 Reliability test

In this study, the reliability of the scale was tested by the dual criteria of Cronbach's coefficient (α) and the corrected item—total correlation (CITC): an α value≥0.7 was considered a qualified criterion (where > 0.9 is excellent), and at the same time, the CITC value 0.4 And the items whose dimension α value increases after deletion need to be deleted. The measured data show that the α coefficients of all variables are significantly higher than the threshold (0.793–0.856, if the performance expectation reaches 0.856), and the CITC of each item and the α values after deletion all meet the requirements, confirming that the scale has stable internal consistency and reliable reliability.

5.2.2 Structural validity tests

Validity test is to test the validity of the questionnaire, refers to the degree to which the means or instrument of measurement can accurately measure things, the more the results of the test are in line with the examination questions, the higher the validity, otherwise the lower the validity. Analyzing the significance and KMO value through SPSS, the significance is less than 0.05, which means that the data of this questionnaire is suitable for doing factor analysis. Following to look at the KMO value, if this value is higher than 0.8, it indicates high validity; if this value is between 0.7 and 0.8, it indicates better validity; if this value is between 0.6 and 0.7, it indicates acceptable validity and if this value is less than 0.6, it indicates poor validity. As shown in Table 3, the results of the test are: the p-value of Bartlett's test is less than 0.05, which indicates that the questionnaire data can be factor analyzed. The KMO value is 0.902 > 0.7, which indicates that the validity is high. This leads to the existence of correlation between the original variables.

In this study, AMOS 24.0 software was used to conduct a confirmatory factor analysis (CFA) on the variables of the Performance Expectation Scale, Effort Expectation Scale, Social Influence Scale, Enablers Scale, Informational Motivation Scale, Perceived Risk Scale, Perceived Cost Scale, and Compatibility Scale covered in this paper, and Composite Reliability (CR) and Average Variance Extracted (AVE) were used to determine convergence of the variable dimensions of the Validity.

The model fit of the validated factor analysis scale was first tested. The data collected from the questionnaire were imported into AMOS 24.0 software and the model fit parameters obtained by applying the maximum likelihood method are shown in Table 4.

As can be seen from Table 4, the value of MIN/DF is 1.024<3, NFI, RFI, IFI, TLI, CFI, GFI are all greater than 0.9, and the RMSEA is 0.006 < 0.08, which indicates that the validated factor analysis of the model fits well, and that the Performance Expectation Scale, Effort Expectation Scale, Social Influence Scale, Enablers Scale, Informational Motivation Scale, Perceived Risk Scale, Perceived Cost Scale, Compatibility Scale, and Willingness to Adopt Scale overall had a good model fit.

As can be seen from Table 5, the standardized factor loadings are greater than 0.50 for each measure between 0.562 ~ 0.604 in the factor analysis model validated in this paper, and the corresponding significant p-values are all less than 0.05, which indicates that there is a significant effect between each latent variable and the observed variables. Meanwhile, the AVE values of mean variance extraction ranged from 0.564 ~ 0.619, all of which were greater than 0.5, and the CR values of joint reliability ranged from 0.794 ~ 0.856, all of which

TABLE 2 Analysis of sample characteristics.

Name	Options	Frequency	Percentage (%)	Cumulative percentage (%)
Enterprise size	Small and microenterprises (number of employees <100, business revenue <20 million yuan)	357	59.20	59.20
	Medium-sized enterprises (100 S employees < 300, 20 million yuan≤ Operating income < 10,000 million yuan)	214	35.49	94.69
	Large enterprises (≥300 employees, business revenue ≥100 million yuan)	32	5.31	100.00
Years of enterprise establishment	0 to 3 years	180	29.85	29.85
	>3 ~ 10 years	301	49.92	79.77
	>10 ~ 30 years	103	17.08	96.85
	>30 years	19	3.15	100.00
Nature of business	Nationalized business	140	23.22	23.22
	Private business	412	68.33	91.54
	Foreign enterprise	51	8.46	100.00
Business model	Food producers	209	34.66	34.66
	Food processor	283	46.93	81.59
	Food marketing and distribution companies	111	18.41	100.00
Add up the total		603	100.0	100.0

TABLE 3 KMO and Bartlett's test table.

Indicator		Result
KMO sample suitability quantity		0.902
Bartlett's test of Sphericity	Approximate chi-square	7322.753
	Degrees of freedom	378
	Significance	0.000

were greater than 0.7, indicating that the convergent validity of the variables of the present study was good.

At the same time, this paper used Amos24.0 to test the data of the measurement model for discriminant validity, as shown in Table 6, it can be seen that the absolute value of the correlation coefficient of the eight variables with other variables is less than 0.9, and all of them are less than the AVE square root value of the variables, and the discriminant validity of the scale is good.

6 Data analysis

This study abandons a single qualitative or quantitative research instrument in favor of a qualitative comparative analysis (QCA) approach based on ensemble theory, aiming to explore in depth the multifaceted influencing mechanisms behind enterprises' willingness to adopt a blockchain-based food safety traceability system from a group perspective. This choice is made mainly based on the following considerations:

First, traditional research methods tend to focus on exploring the independent effects of individual factors or analyzing only simple two-by-two interaction effects between factors. However, to clearly elucidate the formation path of enterprises' willingness to adopt blockchain-based food safety traceability system, it is difficult to explain the mode of action of the complex interdependencies between conditional variables on the results by relying on these traditional means alone. Unlike traditional statistical analysis, the QCA method, through cross-case analysis, treats each enterprise case as a combination of a series of causal conditions, and then compares and examines the nonlinear logical connection between the matching patterns of different conditions and the outcome of enterprise adoption intention.

Second, the QCA methodology is able to identify multiple groups of equivalent conditions that produce the same outcome. In other words, there is not a single path that drives firms' adoption intentions, but rather a variety of paths with equivalent effects, in contrast to traditional analytical approaches that seek a single optimal path. This feature helps us to better understand the different mechanisms that drive adoption intentions in different firms' contexts, so that we can provide firms' practices and policymakers with more targeted intervention strategies.

Finally, the QCA approach is based on an asymmetric logical premise that encompasses causal asymmetry and conditional action asymmetry. It suggests that the conditions under which firms' adoption intentions are generated and not generated may be different, and the same condition may have opposite facilitating or inhibiting effects in different groupings. Compared to the uniformity of causal effects assumed by linear regression, its asymmetry better explains the group-state effects of differences in business cases and dependencies between conditions. Given that the influencing factors are highly dependent and non-independent when enterprises adopt blockchain food safety traceability system, QCA analyzes the comprehensive influencing mechanism from the perspective of overall correlation, which can provide feasible suggestions to enhance enterprises' willingness to adopt.

TABLE 4 Model fit in confirmatory factor analysis.

Model fit	CMIN	DF	CMIN/DF	NFI	RFI	IFI	TLI	CFI	GFI	RMSEA
Fitting result	321.501	314	1.024	0.957	0.948	0.999	0.999	0.999	0.964	0.006
Recommended value			<3	>0.9	>0.9	>0.9	>0.9	>0.9	>0.9	<0.08

TABLE 5 Factor loadings, CR values, and AVE values for measurement models.

Variable	Subject	P	Standardized factor loading	AVE	CR
Performance expectations	PE4		0.788	0.599	0.856
	PE3	***	0.755		
	PE2	***	0.799		
	PE1	***	0.752		
Effort expectations	EE3		0.734	0.566	0.796
	EE2	***	0.752		
	EE1	***	0.770		
Social influence	SI3		0.743	0.562	0.794
	SI2	***	0.741		
	SI1	***	0.765		
Contributing factor	CF3		0.775	0.601	0.819
	CF2	***	0.790		
	CF1	***	0.760		
Informational motivation	IM3		0.778	0.604	0.820
	IM2	***	0.734		
	IM1	***	0.817		
Perceived risk	PR3		0.785	0.597	0.816
	PR2	***	0.782		
	PR1	***	0.751		
Perceived costs	PC3		0.700	0.564	0.795
	PC2	***	0.759		
	PC1	***	0.792		
Compatibility	CC3		0.785	0.600	0.818
	CC2	***	0.756		
	CC1	***	0.783		
Adoption intention	AI3		0.760	0.578	0.804
	AI2	***	0.793		
	AI1	***	0.726		

"***" represents the significance $p < 0.001$, indicating that the confidence of the research resultsare very high.

6.1 Variable assignment and calibration

In this paper, fsQCA method is applied to explore the relationship between the combination of multiple factors affecting enterprises' willingness to adopt blockchain-based food safety traceability system, and the calibration operation is implemented with the help of fsQCA software. In this paper, the anchor points are selected as 4, 3, and 2, because the questionnaire in this paper is a Likert five-level scale, and 4, 3, and 2 are selected as the fuzzy set calibration thresholds for the Likert five-level scale, following the double logic of fsQCA methodological requirements and scale characteristics: firstly, based on the theory of fuzzy sets, it is necessary to set up three breakpoints of complete affiliation (1), intermediate affiliation (0.5), and complete non-affiliation (0), and the five points are set at "4–4" in the scale. In the scale, "4–5", "3" and "1–2" correspond to high, medium and low affiliation levels respectively, of which 4 (including "relatively consistent" and "very consistent") indicates that the case strongly belongs to the target set, 3 ("moderately consistent") reflects the highest level of ambiguity, and 2 (including "relatively inconsistent" and "very inconsistent") signifies that the case essentially deviates

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TABLE 6 Matrix of correlation coefficients between variables.

Variable	Performance expectations	Effort expectations	Social influence	Contributing factor	Informational motivation	Perceived risk	Perceived costs	Compatibility	Adoption intention
Performance expectations	0.774								
Effort expectations	0.446	0.752							
Social influence	0.441	0.484	0.750						
Contributing factor	0.335	0.398	0.363	0.775					
Informational motivation	0.394	0.594	0.370	0.357	0.777				
Perceived risk	−0.521	−0.538	−0.528	−0.400	−0.451	0.773			
Perceived costs	0.324	0.466	0.369	0.310	0.329	−0.529	0.751		
Compatibility	0.410	0.497	0.452	0.391	0.424	−0.449	0.415	0.775	
Adoption intention	0.423	0.489	0.452	0.385	0.425	−0.496	0.406	0.469	0.760

Diagonal values are AVE square root values for each latent variable.

from the target set; second, the threshold continues the calibration paradigm of the seven-point scale (e.g., 6, 4, 2), avoiding log-transformation anomalies by truncating the extremes (5/1), while retaining the intermediate value (3) to maintain the symmetry of the data, and ensuring that the degree of affiliation is in the range of (0,1) interval is continuously distributed. At the theoretical and empirical levels, this setting fits the usual division of five-point scales in psychology and management (4–5 for positive attitudes, 3 for neutrality, and 1–2 for negative attitudes), and has been verified by existing studies, which not only balances data differentiation and fsQCA's demand for conditional portfolio analysis, but also improves the robustness of the results by circumventing the mathematical anomalies, which is in line with the requirements of method transparency and replicability. The calibration information for each variable is shown in Table 7.

6.2 Analysis of necessary conditions

Before analyzing the conditional grouping, it is necessary for the researcher to test the "necessity" of each condition individually, and then to analyze the sufficient conditions for the conditions that cannot be treated as necessary conditions individually, and identify the conditional grouping that has the greatest explanatory power for the target case through Boolean algebra minimization. Therefore, this paper combines mainstream QCA studies to first test whether a single condition constitutes a necessary condition for enterprises' willingness to adopt a blockchain-based food safety traceability system, and the results are shown in Table 8. From the table, it can be seen that: first, the consistency of each condition is relatively high, which has some explanatory power for the results; second, each condition's consistency fell below the strict threshold of 0.9, confirming that no single condition is necessary for adoption intention. This result reveals the complexity of the enterprise's willingness to adopt the blockchain-based food safety traceability system, i.e., performance expectation, effort expectation, social influence, enabling factors, informational motivation, perceived risk, perceived cost, and compatibility need to be linked and matched in order to achieve the best effect. In other words, the enhancement of enterprises' willingness to adopt blockchain-based food safety traceability system should comprehensively consider the concurrent synergistic effects of multiple conditions.

6.3 Sufficiency analysis of conditional groupings

After the analysis of necessary conditions, the construction of the truth table is carried out based on this. In this paper, the consistency threshold is set at 0.85, and it is considered that a PRI consistency greater than 0.9 is regarded as a valid case. In fsQCA analysis, Core Conditions refer to the factors that exist in most high-adoption paths and have a decisive influence on the results. The absence of them will significantly weaken the explanatory power of the combination of conditions. Peripheral Conditions are the factors that assist the core conditions to function in a specific path. Their existence or absence reflects the differentiated characteristics of different paths. This study adopts the definition standard of Ragin and identifies the core

TABLE 7 Calibration information for condition and outcome variables.

Variable type	Variable name	Complete affiliation	Cross-over point	Complete non affiliation
Conditional variable	Performance expectations	4.00	3.00	2.00
	Effort expectations	4.00	3.00	2.00
	Social influence	4.00	3.00	2.00
	Contributing factor	4.00	3.00	2.00
	Informational motivation	4.00	3.00	2.00
	Perceived risk	4.00	3.00	2.00
	Perceived costs	4.00	3.00	2.00
	Compatibility	4.00	3.00	2.00
Outcome variable	Adoption intention	4.00	3.00	2.00

TABLE 8 Analysis of necessary conditions.

	High adoption intention		Low adoption intention	
Conditional variable	Consistency	Degree of coverage	Consistency	Degree of coverage
Performance expectations	0.74	0.86	0.58	0.19
~Performance expectations	0.30	0.72	0.57	0.38
Effort expectations	0.82	0.87	0.62	0.18
~Effort expectations	0.23	0.68	0.55	0.46
Social influence	0.85	0.87	0.65	0.19
~Social influence	0.20	0.67	0.53	0.50
Contributing factor	0.79	0.88	0.58	0.18
~Contributing factor	0.26	0.69	0.60	0.45
Informational motivation	0.83	0.86	0.65	0.19
~Informational motivation	0.21	0.69	0.50	0.45
Perceived risk	0.20	0.66	0.55	0.50
~Perceived risk	0.84	0.87	0.62	0.18
Perceived costs	0.84	0.86	0.64	0.18
~Perceived costs	0.21	0.67	0.52	0.47
Compatibility	0.84	0.86	0.63	0.18
~Compatibility	0.21	0.67	0.53	0.48

"~" indicates that the variable does not exist or has a low level of influence.

conditions through Boolean minimization. The specific symbol definitions are as follows: the edge conditions are indicated by the symbol "●." When the core condition is missing, it is denoted by "⊗"; when the variable has no effect on the result, it is denoted by a space. The final output of the group path analysis is shown in Table 9. The fsQCA truth table can be referred to in Appendix A.

Original coverage is the percentage of all antecedent combinations for which this path is shown in the results; unique coverage is the percentage that is not covered by other combinations of paths; solution coverage measures the degree to which the complete solution explains the occurrence of the results; solution consistency indicates the degree to which the explanatory affiliation of this path is a subset of the resultant occurrences, and in general sets the lower value of consistency at 0.75. This paper obtains a total of 5 paths, and the consistency of all 5 paths is above 0.9 and higher than 0.75, indicating that the paths are all better able to explain the occurrence of high adoption intentions. In addition, the consistency of the solution of the overall condition combination is 0.96, which is higher than 0.75, indicating that the overall solution has better consistency.

7 Results

7.1 Configuration analysis

Path 1 (~PE* EE* SI * IM * ~ PR * PC * ~ CC). ~PE denotes lower performance expectation, EE denotes higher effort expectation, SI denotes higher community impact, IM denotes higher informational motivation, ~PR denotes lower perceived risk, PC denotes higher perceived cost, and CC denotes lower compatibility. This path shows that although enterprises have limited expectations for the system to improve operational efficiency, the ease of operation reduces internal resistance, the industry demonstration effect creates external thrust, and there is a strong demand for data transparency. Despite the high

TABLE 9 Sufficient conditions analysis of firms' willingness to adopt blockchain-based food safety traceability system.

	High adoption intention				
Conditional variable	Path 1	Path 2	Path 3	Path 4	Path 5
Performance Expectations (PE)	⊗	●	●	⊗	●
Effort Expectations (EE)	●	●	⊗	⊗	●
Social Influence (SI)	●	●	⊗	●	●
Contributing Factors (CF)	●	●	●	●	●
Informational Motivation (IM)	●	⊗	●	●	●
Perceived Risk (PR)	⊗	⊗	⊗	⊗	⊗
Perceived Costs (PC)	●	⊗	●	●	●
Compatibility (CC)	⊗	●	●	●	●
Original coverage	0.044	0.037	0.040	0.042	0.355
Unique coverage	0.016	0.012	0.011	0.009	0.322
Overall consistency	0.965	0.981	0.971	0.975	0.956
Coverage of solutions	0.41				
Consistency of solutions	0.96				

cost of introduction and the difficulty of integration, the synergy of the three factors makes enterprises willing to adopt the system even when the value is not sufficiently recognized. The path reflects the logic of "passive following" led by the external environment and ease of use.

Path 2 (PE* EE* SI* CF* ~ IM* ~ PR* ~ PC* CC): PE denotes higher performance expectation, EE denotes higher effort expectation, SI denotes higher social influence, CF denotes higher contributing factors, ~IM denotes lower informational motivation, ~PR denotes lower perceived risk, ~PC denotes lower perceived cost, and CC denotes higher compatibility. This path shows that companies that recognize the value of the system, have mature external conditions, and have low resistance to implementation have a strong willingness to adopt the system even if they have low informational motivation. This is a typical logic of "combination of advantageous conditions," which reflects the synergy between intrinsic value judgment and external guarantee in technology adoption.

Path 3 (PE* ~ EE ~ SI*CF*IM* ~ PR*PC *CC). PE denotes higher performance expectations, ~EE denotes lower effort expectations, SI denotes lower social influence, CF denotes higher and lower contributing factors, IM denotes higher informational motivation, ~PR denotes higher perceived risk, PC denotes higher perceived cost, and CC denotes higher compatibility. This path shows that higher performance expectations and higher informational motivation are at the core, and compatibility mitigates multiple resistances. Despite the complexity, lack of demonstration, higher cost, and higher perceived risk, organizations are willing to try despite the disadvantages due to the certainty of the system's strategic value, data-driven needs, and the feasibility of technology integration. This reflects a "value-first, risk-compromise" approach to decision-making.

Path 4 (~PE* ~ EE*SI*CF* IM* ~ PR*PC*CC). ~PE denotes lower performance expectation, ~EE denotes lower effort expectation, SI denotes higher social influence, CF denotes higher contributing factors, IM denotes higher informational motivation, ~PR denotes lower perceived risk, PC denotes higher perceived cost, and CC denotes higher compatibility. This path shows that enterprises are passively driven by industry synergistic pressure or internal resource support within the enterprise, and at the same time need to improve transparency through data. Although the system is considered to have limited direct benefits and complex operation, lower perceived risk and higher compatibility ease implementation resistance, and even though enterprises have lower expectations, industry ecological pressure and enterprise's internal conditions still drive adoption.

Path 5 (PE*EE*SI*CF* IM* ~ PR *PC *CC) PE indicates higher performance expectations, EE indicates higher effort expectations, SI indicates higher social influence, CF indicates higher contributing factors, IM indicates higher informational motivation, ~PR indicates lower perceived risk, PC indicates higher perceived cost, and CC indicates higher compatibility. This path is the ideal configuration, combining higher performance expectations, higher effort expectations, higher social influence, higher enablers, higher informational motivation, and lower perceived risk, with only higher perceived cost balanced by higher compatibility. Enterprises fully recognize the value of the system in enhancing efficiency and quality. Its convenient operation promotes employee acceptance; industry trends strengthen the necessity; internal support within enterprises reduces the difficulty of implementation; strong demand for data-driven decision making, and there are no security concerns. Although the initial investment is high, the seamless integration of the system ensures the feasibility of implementation.

7.2 End results analysis

In the fsQCA grouping analysis, if the core conditions do not form a unified existence across the paths (i.e., each path consists of only edge conditions or the absence of edge conditions), it essentially reflects the fact that the enterprise's decision to adopt the blockchain food safety traceability system is the result of the synergistic action of multiple edge conditions, rather than relying on a single core factor. Combined with the specific performance of the five paths, it can be analyzed as follows.

The absence of core conditions in traditional fsQCA does not mean that the explanatory power is weakened, but rather reveals "condition combination equivalence"—i.e., different combinations of marginal conditions can achieve high adoption intentions through synergistic effects. The specific features are as follows:

7.2.1 "Contextual dominance" of marginal conditions

External Pressure-driven combination (Paths 1 and 4): With "social influence (SI) + contributing factors (CF)" as the core marginal condition, supplemented by informational motivation (IM). Among them, social influence (SI) directly reflects external institutional pressures such as industry benchmark demonstrations and partner adoption, constituting the core external driving force for enterprise adoption. Contributing factors (CF) focus on internal resource support within an enterprise (such as funds, technical training, and management commitments), but their role is to provide internal execution guarantees in response to external pressure, forming a chain logic of "external trigger—internal execution." This combination embodies the compound driving force of "external pressure—internal resource response—imitation and following."

Internal Value-driven combination (Paths 2 and 5): Relying on internal edge conditions such as "Performance Expectation (PE) + Effort Expectation (EE) + Informational Motivation (IM)," such as the superposition of higher Performance Expectation (PE) and higher Effort Expectation (EE) in Path 2, and the multiple positive edge conditions (PE, EE, SI, CF, IM) in Path 5 to form the "ideal grouping," reflecting the active recognition of the system value by the enterprise.

Contradiction-balancing combination (Path 3): There are both positive factors (PE, IM, CC) and negative factors (~EE* ~ SI*PC) in the edge conditions, but the resistance to integration is mitigated by high compatibility (CC), reflecting the balanced logic of "immediate need for value—controllable risk".

7.2.2 "Compensatory mechanisms" for the absence of conditions

The absence of marginal conditions (e.g., ~PE, ~IM) can be compensated by the reinforcement of other conditions: low performance expectation (~PE) in Path 1 is compensated by high community impact (SI) and informational motivation (IM)—even if the enterprise perceives the system as having limited direct value, it still adopts it due to the competitive pressure of the industry and the need for data; Path 2 Medium-low Informational Motivation (~IM) is compensated by low Perceived Risk (~PR), low Perceived Cost (~PC), and high Compatibility (CC)—organizations do not need to be data-driven, but only have to adopt due to low resistance and high adaptability.

7.3 Robustness tests

After analyzing the five combined paths, the robustness of the combined paths also needs to be verified. In this paper, the consistency threshold in the truth table is raised from 0.85 to 0.95, and other settings remain unchanged, and the combined paths of the enterprise's willingness to adopt the blockchain-based food safety traceability system are re-computed. In the re-computation results of the combined path, the consistency, coverage, and the composition of the combined path do not change, and the results of the re-computation are consistent with the pre-validation (Table 9). It can be seen that the results of the five combined paths obtained through the arithmetic analysis in this paper are robust.

8 Conclusions and recommendations

8.1 Conclusion

Based on the UTAUT model, this study utilizes the fsQCA method to reveal the complex impact mechanisms of corporate adoption of blockchain-based food safety traceability systems, and the main conclusions are as follows.

8.1.1 Driven by multiple factors, with no single necessary condition

Adoption intention of enterprises is influenced by the interaction of multi-dimensional factors such as Performance Expectation (PE), Effort Expectation (EE), Social Influence (SI), Facilitating Factors (CF), Informational Motivation (IM), Perceived Risk (PR), Perceived Cost (PC), Compatibility (CC), etc., and there is no single determining condition. The factors form a synergy through "concurrent synergy," e.g., higher performance expectations need to be matched with lower perceived risk and higher compatibility in order to effectively promote adoption, which highlights the importance of the linkage of the multidimensional factors in the application of the system.

8.1.2 The adoption path presents multiple driving logic

Through group analysis, the study distills five equivalent paths of high adoption intentions, reflecting the synergistic effects of different combinations of conditions:

External Pressure Type (Path 1 and 4): Relying on high social influence and high contributing factors, even if the enterprise's own performance expectations and effort expectations are low, it still adopts through external thrust and informational motivation, reflecting the logic of "Institutional Pressure-Imitation and Followership." This reflects the "institutional pressure-imitation-following" logic.

Internal value (Path 2 and 5): Taking higher performance expectations as the core, superimposed with higher effort expectations, higher social influence, higher contributing factors and other positive conditions, reflecting the enterprise's proactive recognition of the system to improve operational efficiency, quality control, and the formation of "intrinsic value + internal support" for strong adoption of power.

Contradictory balance type (path 3): Higher performance expectations and higher informational motivation break through the operational barriers of lower effort expectations and the lack of external demonstration of lower social influence, and alleviate integration resistance through higher compatibility, reflecting the balanced decision-making logic of "immediate need for value-controllable risk".

8.1.3 The asymmetric effect of perceived risk and cost is significant

Perceived Risk (PR): Higher perceived risk (e.g., data breaches, compliance pressures) directly undermines willingness to adopt, while low perceived risk is a necessary foundation of trust for adoption, the absence of which creates a psychological barrier.

Perceived cost (PC): While higher perceived costs are prevalent in most pathways, they can be offset by conditions such as high compatibility (lower integration costs), high enablers (enterprise internal support), or strong informational motivation (data value-driven), with the key being a comprehensive assessment of cost-effectiveness.

8.1.4 International comparative insights into adoption mechanisms

A comparison between the five paths identified in this study and international cases reveals the following. The external pressure-driven paths are highly analogous to the EU model. For instance, German meat enterprises adopt blockchain systems due to mandatory requirements from retailer alliances (Singh et al., 2023). Despite high perceived costs (PC), low perceived risks (~PR) compliant with GDPR and supply chain collaboration (high CF) facilitate passive adoption. The internal value-driven paths are exemplified in Australia's wine industry, where the leading enterprise Penfolds enhances brand premium through blockchain traceability (high PE), and its technological compatibility (high CC) reduces integration difficulties for wineries, forming a dual-drive of "value-usability." The contradiction-balancing path mirrors the dilemmas of smallholders in ASEAN. Thai coffee producers recognize the value of traceability (high PE) but are constrained by operational complexity (low EE) and cost pressures (high PC). However, it has achieved a risk balance by establishing an industry alliance chain led by the government, confirming that compatibility (CC) compensates for negative conditions (Tharatipyakul et al., 2022). In summary, internationally, perceived risk (PR) serves as a key inhibitory factor in strictly regulated regions such as EU, while in loosely regulated regions such as Southeast Asia, it is replaced by cost (PC) and effort expectancy (EE) and Compatibility (CC) consistently acts as a "lubricant" for cross-regional adoption.

8.2 Recommendations

Based on the above research conclusions, combined with the multiple driving logics and differentiated path characteristics of enterprises adopting blockchain-based food safety traceability systems, targeted suggestions are put forward from the following aspects:

First, strengthen the synergy of multiple driving factors and build a full-chain support system. Technology suppliers need to enhance the core value and ease of use of the system, strengthen enterprise performance expectations through case visualization, and develop intelligent analysis modules. For the operational threshold issues expected in efforts, develop traceability systems such as those divided into procurement, production, and circulation modules, support "compatibility" integration with the enterprise's existing ERP or other systems, and reduce employee training costs through low-code development (Bhat et al., 2021). Industry associations and regulatory authorities should collaborate with government resources, promote benchmark cases, and jointly stimulate the driving force within communities and enterprises to lower the implementation threshold for the entire industry.

Second, implement precise intervention strategies in response to differentiated adoption paths. For large enterprises, guide them to integrate traceability systems with brand strategies to enhance supply chain efficiency, and improve supply chain management efficiency through performance expectations and informational motivations to reduce quality control costs. Small, medium and micro enterprises purchase technical services in packages through industry associations, providing "one-stop" traceability solutions (Zhong et al., 2024; Kamarulzaman et al., 2022). For foreign-funded and export-oriented enterprises, international traceability standard adaptation services are provided to meet the compliance needs in perceived risks, helping enterprises comply with the regulatory requirements of exporting countries and avoid trade barriers (Liao and Xu, 2019).

Third, optimize perceived risks and cost expectations. At the level of trust building, a security certification system should be established, technical information should be disclosed publicly, and enterprises should be encouraged to join industry alliance chains. For instance, by referring to the government alliance chain model of Thai coffee, a "1 + N" alliance chain architecture should be promoted in high-frequency risk categories such as fresh produce and grains and oils, that is, one core enterprise takes the lead and *N* upstream and downstream enterprises participate (Zhang et al., 2023). The distributed storage of the consortium chain reduces the technical investment pressure on individual enterprises and simultaneously enhances the efficiency of data sharing. At the cost adjustment level, develop open-source cost–benefit analysis tools to quantify benefits and inputs, implement the "government-enterprise shared responsibility" model, reduce cost resistance on both the adoption and supply sides, and enhance technical feasibility.

8.3 Research limitations

8.3.1 Limited generalizability beyond China's food industry

The current study focuses on food enterprises in China, and the research findings may face challenges in generalizing to other industries or national contexts. China's unique policy environment (e.g., the "14th Five-Year National Food Safety Plan") and industrial structure shape specific adoption motivations that may not align with those in developed economies or non-food sectors. For instance, enterprises in countries with less mature blockchain regulatory frameworks might prioritize technical feasibility over policy compliance, while manufacturing industries may emphasize operational efficiency over supply chain transparency. Future studies could compare cross-industry or cross-national samples to validate the model's universality.

8.3.2 Potential biases in self-reported data

The research relies on self-administered questionnaires, which may introduce response biases such as social desirability (enterprises overstating adoption willingness to comply with policy expectations) or recall errors (inaccurate assessments of technical costs). Although reliability tests (Cronbach's $\alpha > 0.7$) and validity checks (KMO = 0.902) were conducted, self-reported data cannot fully replace objective performance metrics. For example, perceived risk scores might be underestimated due to enterprises' limited technical literacy. In the follow-up, a hybrid method can be used to combine the survey with the systematic use of data or interviews to cross verify the research results.

8.3.3 Gap between adoption intention and actual behavior

The study measures "willingness to adopt" rather than tracking real-world implementation, leaving a research gap in the intention-behavior consistency. As shown in Path 5, high intention under ideal conditions may not translate to action due to unforeseen barriers like sudden cost increases or technical glitches. Subsequently, vertical design can be adopted to observe the adoption behavior of enterprises within 1 to 3 years to clarify whether the intention can effectively predict the implementation situation, especially for SMEs with constrained resources.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JZ: Funding acquisition, Writing – review & editing, Resources, Supervision, Conceptualization. ZC: Methodology, Data curation, Investigation, Writing – original draft, Formal analysis. XQ: Visualization, Conceptualization, Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. Joint Research Program of LiaoNing Provincial Science and Technology Plan (Grant No. 2024-MSLH-030); LiaoNing Revitalization Talents Program (Grant No. XLYC2410032).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1637246/full#supplementary-material

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