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How does digital transformation drive innovation in Chinese agribusiness: Mechanism and micro evidence

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ABSTRACT

This paper investigates the impact of digital transformation on innovation within the agribusiness sector, both theoretically and empirically, through an examination of Chinese A-share agriculture-related listed companies spanning from 2011 to 2021. The findings suggest that digital transformation significantly enhances innovation capability of agribusiness, while concurrently fostering improvements of its innovation quality. These results hold robust following an endogeneity test and a series of robustness tests. Our heterogeneity analysis found that digital transformation exerts a more pronounced influence on promoting innovation among state-owned agribusinesses, those located in the eastern region of China, and those facing heightened financing constraints. Mechanism testing revealed that digital transformation not only enhances the technological capabilities of agribusiness but also alleviates their financial constraints, thereby facilitating the convergence of innovative resources such as technology, talent and capital to agribusiness, and consequently elevating agribusi-ness innovation levels. This paper elucidates the impacts and mechanisms of digital transformation on agribusiness innovation, offering valuable insights for decision-makers aiming to foster agribusiness innovation, particularly in developing nations.

Introduction

Since the onset of the new millennium, China's agricultural development has encountered numerous challenges, including accelerated urban labor migration, limited arable land resources, increasingly stringent ecological and environmental constraints, as well as a complex and volatile international trade landscape. It is imperative to expedite the transformation of China's agricultural development model to an innovation-driven approach. Agribusinesses play a pivotal role in driving propelling innovation in the field of agricultural science and technology. Despite the substantial number of Chinese agribusinesses, their ability of scientific and technological innovation is not strong (Zhang et al., 2021). Urgent breakthroughs are needed in the development of core seed sources, agricultural machinery and equipment, and other key agricultural technologies.

Promoting innovation in agribusiness has emerged as a critical imperative for China's agricultural development. Existing studies have shown that digitization, as a novel developmental paradigm (Peng & Tao, 2022), expedites the integration and restructuring of digital resources with traditional resources, thereby transforming the interplay between production factors and their combination (Meng & Wang, 2023). Digitization also facilitates enterprise innovation (Zhuo & Chen, 2023), strengthens enterprise competitiveness (Kamalaldin et al., 2020), and has become an inevitable trend of enterprise development (Warner & Wager, 2019). However, the majority of existing studies have primarily focused on manufacturing firms, with relatively little attention paid to agribusiness.

In 2023, the Chinese government released the Overall Layout Plan for the Construction of Digital China, underscoring the acceleration of digital technology adoption across critical sectors like agriculture and energy, while also promoting the in-depth integration of digital technologies and the real economy. In recent years, Chinese agribusinesses have gradually begun to apply digital technologies across their production, processing, distribution, and services chains. While most studies demonstrate that digital transformation fosters innovation and facilitates growth, an opposing perspective suggests that it is not an easy task, with many companies struggling to realize favorable financial returns (Tabrizi et al., 2019; Wade & Shan, 2020). Against this policy backdrop, a pivotal question arises: can digital

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transformation indeed spur innovation within Chinese agribusinesses? Agribusinesses, as traditional enterprises, often encounter substantial challenges during digital transformation, including inadequate capital resources and scarcity of skilled personnel. Therefore, it is imperative to elucidate the impact of digital transformation on innovation in Chinese agribusiness and its underlying mechanisms to promote the digital transformation and the high-quality development of traditional enterprises such as agribusinesses, a task of both theoretical and practical significance.

This study presents three major contributions to the existing literature. First, while previous research on digital transformation has primarily focused on manufacturing enterprises, this paper aims to explore the impact and mechanisms of digital transformation in promoting innovation within traditional agribusinesses. By expanding the scope of research on digital transformation, we hope to contribute to a more comprehensive understanding of its potential benefits. Given China's status as the world's largest developing country, it can serve as a model for other developing nations seeking to improve agribusiness innovation. Second, we delve deeper into examining the impacts of digital transformation on the quality of innovation in agribusiness. Third, based on the fundamental developmental characteristics of agribusiness, we examine the specific pathways through which digital transformation impacts agribusinesses, encompassing both technological and financial perspectives. This endeavor enriches our comprehension of the relationship between digital transformation and enterprise innovation.

The remaining sections of the paper are structured as follows. Section 2 provides a comprehensive review of the existing literature. Section 3 presents the development of our hypotheses. In Section 4, we describe our data and provide an econometric specification. The empirical results are presented in Section 5. Finally, Section 6 concludes the paper by offering policy implications.

Literature review

The influencing factors of enterprise innovation

Innovation stands as a pivotal catalyst for economic development, sparking a vibrant academic discourse surrounding the determinants of firm innovation (Sun, Fang, Li, & Wang, 2024). In early research, Schumpeter (1942) posited that technological innovation primarily emanates from large monopolistic firms, asserting a proportional relationship between industry monopoly, firm size, and innovation. Subsequent scholars have extensively tested the validity of these aforementioned hypotheses through numerous empirical examinations, with particular emphasis on exploring the relationship between market structure and firm innovation. Numerous studies have been conducted to investigate the relationship, considering factors such as the degree of product market competition (Aghion et al., 2005), trade globalization, import competition (Bloom et al., 2015), and foreign competition (Autor et al., 2020). Nonetheless, these inquiries have yielded inconclusive findings, highlighting the complexity of the relationship between market structure and firm innovation. Moreover, the interface between industrial policy and enterprise innovation remains a focal point of research. Considering the externalities associated with innovation (Nelson, 1959; Arrow, 1962), governments have introduced supportive policies aimed at reducing the costs and risks of enterprise innovation, such as government subsidies (Lach, 2002), tax breaks (Jia & Ma, 2017), etc. These measures have effectively promoted enterprise innovation (Sun, Fang, Li, & Ai, 2024). In short, the determinants of enterprise innovation are multifaceted, encompassing diverse factors. Relatively few empirical studies have specifically focused on agribusiness, although some studies have examined the impacts of business diversification, climate policy uncertainty (Li et al., 2024), and regulatory mechanisms (Jiang & Zhou, 2020) on the innovation benefits of agribusiness.

The impact of enterprise digital transformation

The relationship between digital transformation and firms' production and operation behavior has been richly discussed by academics, who have also explored topics such as firms' operational efficiency (Tian et al., 2023), financial distress (Cui & Wang, 2023; Chen et al., 2024), CSR (Lin & Zhang, 2023), carbon intensity (Shang et al., 2023), environmental performance (Xu et al., 2023), and total factor productivity (Zhang et al., 2023a). Across these domains, a prevailing consensus emerges: digital transformation is beneficial to corporate development. Notably, the relationship with enterprise performance has garnered significant attention, with a majority of studies affirming the advantageous impact of digital transformation on fostering enterprise performance (Zhai et al., 2022; Li et al., 2022a). These studies suggest that digital transformation enhances performance by reducing costs, increasing efficiency, and promoting innovation (Peng & Tao, 2022), and catalyzing business model innovation (Zhang et al., 2023b).

The impact of digital transformation on enterprise innovation

With the rapid growth of the digital economy, enterprises have progressively embarked on digital transformation initiatives. Exploring the nexus between digital transformation and enterprise innovation has emerged as a prominent area of inquiry within innovation research. While the majority of studies indicate a positive impact between digital transformation and firm innovation (Liu et al., 2023a; Li et al., 2023b; Zhang & Liu, 2023), a limited body of literature posits that digital technologies may exert negligible influence on innovation performance, and excessive reliance on them could potentially hinder long-term innovative capabilities (Usai et al., 2021). The mechanisms underlying the impact of digital transformation on enterprise innovation can be summarized as follows: firstly, it reduces the cost of information acquisition for firms (Meng & Wang, 2023); secondly, it facilitates interactions and knowledge exchange among firms and between firms and consumers thirdly, it optimizes business processes for firms (Garzoni et al., 2020); fourthly, it enhances firms' capacity to absorb knowledge or technology (Zhuo & Chen, 2023); fifthly, it optimizes the allocation of production factors (Gao et al., 2023); and finally, it strengthens firms' risk-taking capacity (Liu, Li, & Wang, 2023). Additionally, some studies have also focused on the impact of digital transformation on green innovation in enterprises (Ning et al., 2023; Tang et al., 2023; Lin & Xie, 2024). Digital transformation enhances the absorptive, innovative and adaptive capacities of enterprises in the data analysis, data operation, and data empowerment stages respectively, thereby promoting low carbon technology innovation (Yang et al., 2023).

To summarize, most existing studies have focused on manufacturing enterprises as examples. However, it is essential to recognize that different industries possess unique characteristics, raising questions about whether digital transformation can bring positive impacts to all industries. Furthermore, while high levels of innovation are crucial for long-term enterprise development, there is a lack of academic exploration into the effects of digital transformation on innovation quality within enterprises. Lastly, the precise mechanism by which digital transformation affects agribusinesses innovation remains unclear in existing research. This paper aims to address these gaps in current literature.

Theoretical analysis

According to the theory of endogenous growth, innovation stands as the fundamental driving force behind economic development

(Aghion & Howitt, 1992; Romer, 1990). Governments worldwide are increasingly focused on fostering enterprise innovation. However, achieving high-quality innovation in enterprises necessitates significant and sustained capital investment, coupled with a strong foundation in research and development. Agribusinesses, reliant solely on themselves to achieve such innovation face significant pressure. Resource dependence theory emphasizes the imperative for organizations to acquire resources from their surrounding environment and underscores the need for interdependence and interaction with this environment as a means of promoting enterprise development. This paper argues that the utilization of digital technology can enhance enterprise opportunities to foster relationships with the external environment (Cenamor et al., 2019). Digitization can also bolster enterprise innovation by expediting the dissemination of information, technology, capital, and other essential factors crucial for innovation.

The application of digital technology and the dissemination of digital knowledge can significantly enhance information transparency, enabling enterprises to acquire R&D innovation information at a low cost and with high efficiency (Meng & Wang, 2023). Agribusinesses can accurately analyze potential user needs based on market changes, promptly adjust R&D direction (Zhuo & Chen, 2023), and better serve to upstream and downstream enterprises, as well as customers. Moreover, digitization empowers companies to effectively disseminate information and knowledge through digital channels, thereby facilitating knowledge exchange among stakeholders (Bharadwaj et al., 2013; Kamalaldin et al., 2020). This expedites the flow of knowledge and technology across various networks, enhancing the enterprise's capacity to undergo technological transformations (Zhuo & Chen, 2023), ultimately streamlining the conversion of information and knowledge into high-quality innovations (Paunov & Rollo, 2016).

The utilization of digital technology not only enhances the absorptive capacity of agribusiness, but also fosters the profound integration of digital technology into production and management activities. This integration process strengthens the inherent innovative research and development capabilities of agribusiness itself (Ning et al., 2023). Moreover, the digital economy emphasizes cross-border knowledge as a source of innovation, accelerating the iteration process and subverting traditional innovation models while enhancing accuracy and effectiveness in decision-making (Li et al., 2022b). The combination of fundamental digital technology and industry-specific technology fosters a robust spillover effect, stimulating enterprises to pursue breakthrough innovation (Mikalef et al., 2018). Therefore, agribusiness can proactively leverage the benefits of digital technology to enhance both the quantity and quality of innovation within their operations.

H1: Digital transformation facilitates the enhancement of both quantity and quality of innovation in agribusiness.

The pursuit of enterprise innovation often requires significant capital investment. However, imperfections in the capital market pose challenges for enterprises in securing adequate funds for research and development from the financial market. Leading to constraints on financing (Hall, 2002). Agribusinesses, in particular, confront significant agricultural risks and often lack collateralized assets, resulting in low credit ratings and difficulties in obtaining support from financial institutions.

The implementation of digital transformation in agribusiness has the potential to alleviate financing constraints through two primary mechanisms. Firstly, the digital advancement of agribusiness can improve the production process and optimize business operations (Garzoni et al., 2020). Digitization can also support the integration of the supply chain and promote the optimization of the supply chain structure. This digitization process enhances collaboration across departments and hierarchical levels, optimizing production efficiency and reducing operational costs (Peng & Tao, 2022; Singh et al., 2021). The reduction in operational costs facilitates the augmentation of internal capital, enabling greater investment in research and development.

Secondly, the Chinese government advocates for digitalization, and agribusinesses that pioneer digital transformation are actively aligning with national policy objectives. Such enterprises may receive additional resources and benefit from preferential policies offered by the government and related agencies, thereby alleviating internal funding pressures (Cui & Wang, 2023). Simultaneously, a significant information asymmetry exists between enterprises and the government, posing challenges for accurately identifying enterprises genuinely in need of support. Adopting a merit-based approach to select support targets can enhance policy efficiency and counteract this concern (Howell, 2017). Recently, digital transformation has emerged as a strategy for gaining a competitive advantage (Ferreira et al., 2019). Companies leading in digital transformation are better equipped to grasp the cutting-edge direction of the market, exhibiting stronger market development prospects, reducing information asymmetry between firms and governments, and increasing the likelihood of receiving government attention and support (Yu et al., 2023). By taking advantage of digital transformation, agribusiness can secure additional funds from both internal and external sources, thereby mitigating enterprise financing constraints and subsequently fostering enterprise innovation (As shown in Fig. 1). Building upon the above analysis, this paper proposes research hypothesis 2.

H2: Digital transformation of agribusiness alleviates financing constraints by reducing enterprise operating costs and increasing government subsidies, thereby stimulating agribusiness innovation.

The innovation capacity of China's agribusiness is relatively limited (Zhang et al., 2021), with the quantity and quality of R&D personnel directly impacting this capacity. As agribusinesses embark on digital transformation, there is an increased demand for digital talents to support the realization of this transformation. The addition of new talents will further strengthen the R&D team and facilitate more scientific and technological innovation. For agribusiness, the utilization of digital technology can integrate fundamental digital technologies with enterprise-specific technologies, fostering a robust spillover effect of technological advancements (Mikalef et al., 2018). Simultaneously, the utilization of information technology facilitates communication between upstream and downstream firms (Urbinati et al., 2020), enabling efficient data collection on the demands of consumers and downstream firms, which is an important source of innovation for firms (Li et al., 2022b). After the digital transformation of agribusinesses, incorporating new elements into their innovation efforts will generate a heightened demand for innovation within these enterprises. Consequently, this increased need for innovation necessitates a greater number of R&D personnel to support its realization. As a result, the demand for R&D personnel in agribusinesses is further propelled, thereby fostering an environment conducive to agricultural enterprise innovation.

Collaborating with other enterprises or scientific research institutions proves to be an effective approach to mitigate technological barriers that hinder innovation. The utilization of digital technology in agribusiness further contributes to the reduction of information asymmetry between collaborating parties, thus enhancing alignment with cooperative objectives. Additionally, low-cost digital transactions can foster collaboration among innovative organizations (Goldfarb & Tucker, 2019). The utilization of digital technology also lowers communication costs between agribusinesses and other cooperative entities, thereby facilitating scientific research and collaboration. Additionally, digital technology expands organizational boundaries and facilitates inter-organizational knowledge transfer (Cennamo et al., 2020), which promotes innovation development in agribusiness. Based on this analysis, we propose the following hypothesis:

H3: The digital transformation of agribusiness facilitates innovation by expanding their R&D teams and reinforcing external technical collaborations.

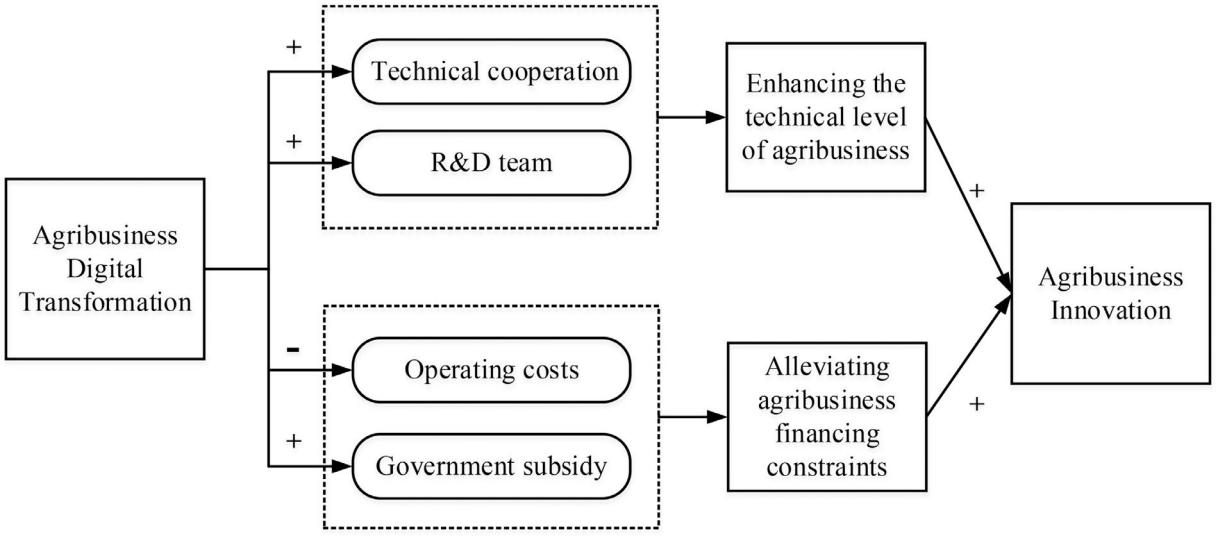

Fig. 1. Mechanism roadmap.

Methodology and data

Methodology

Since this paper uses micro-panel data from 2011 to 2021, in order to further control the influencing factors that do not change over time, we used a multidimensional fixed-effects model for empirical testing (Liu et al., 2023):

$$Patent_{it} = \alpha_0 + \alpha_1 DigitalTransformation_{i,t-1} + \alpha_2 X_{i,t-1} + \mu_i + \mu_t + u_p + \varepsilon_{i,t-1} \quad (1)$$

In Eq. (1), the subscripts i and t denote the agribusiness and year, respectively. The explanatory variable $Patent_{it}$ is the total number of patents filed by agribusiness i in year t. Considering the lagged nature of digital transformation affecting agribusiness innovation, we lagged all the variables affecting agribusiness innovation by one period. The core explanatory variables are $DigitalTransformation_{i,t-1}$ denoting the degree of digital transformation of agribusiness in year $t-1$. $X_{i,t-1}$ is the ensemble of relevant control variables affecting innovation in agribusinesses. μ_i, μ_p, and μ_y are the industry, province, and year fixed effects, respectively, and $\varepsilon_{i,t-1}$ is the random perturbation term.

Sample selection and data sources

This paper takes agriculture-related A-share listed companies from 2011 to 2021 as the research object. This includes eight sub-industries: agriculture industry; forestry industry; animal husbandry industry; fishery industry; agricultural services industry; farm and sideline food processing; food manufacturing industry; and wine, beverage, and refined tea manufacturing industry. The firm-level data are all from the China Stock Market & Accounting Research Database, and the firm patent data are from the Chinese Research Data Services Platform database. We adjusted the data in the following ways: (1) abnormal enterprise samples such as ST and *ST were excluded; (2) corresponding missing-value samples were removed; and (3) continuous variables at the 1 % and 99 % levels were Winsorized to eliminate outliers. Ultimately, a total of 1604 valid observations were obtained.

Variable definition

Independent variables: agribusiness innovation

Drawing on the studies by Chang et al. (2015), and Zhang and Liu (2023), this paper employs the number of patent applications filed by firms as a metric to assess the innovation capacity of agribusiness. By utilizing patent data, this approach not only quantifies the extent of innovation activities, but also provides insights into their quality. Compared to utility model and design patents, invention patents possess a higher degree of technological sophistication (Liu et al., 2021). Because of this, the quality of innovation in agribusiness can be effectively assessed through the applications of invention patents (Ju et al., 2023).

Dependent variables: digital transformation of agribusiness

Referring to the research conducted by Chen (2022) and Zhuo and Chen (2023), we utilize the frequency of keywords associated with digital transformation in the annual reports of listed agricultural enterprises to depict the extent of enterprise-level digital transformation.

In the process of text mining, we categorized enterprise digital transformation into four dimensions: artificial intelligence, blockchain, cloud computing, and big data. Corresponding keywords have been assigned to each dimension. Based on the keywords listed in Table 1, we utilized Python software to systematically search through previous years' annual reports of agricultural enterprises and tallied the total frequency of corresponding key feature words that appeared within them. This indicator was then used to measure the level of digital transformation achieved by these companies.

Control variable

In order to control other relevant factors affecting firms' innovation, this paper refers to Liu et al. (2023b) and Huang and Yuan (2021), and selects firm size; firm age; assets and liabilities; institutional investor shareholding ratio; shareholding ratio of the first largest shareholder; percentage of independent directors; capital expenditures; firm cash flow; return on firm assets; firm ownership; and fixed asset ratio as control variables. The specific meanings of the variables are detailed in Table 2.

Descriptive statistics and correlation analysis

Fig. 2 illustrates the increasing degree of digital transformation in agribusinesses, which can be attributed to the "Internet Plus" strategy

Table 1
Keywords reflecting enterprise digital transformation.

Screening index	Keywords
Artificial Intelligence Technology	Artificial intelligence, Business intelligence, Image understanding, Investment decision aid system, Intelligent data analysis, Intelligent robotics, Machine learning, Deep learning, Semantic search, Biometrics, Face recognition, Voice recognition, Identity verification, Autonomous driving, Natural language processing, Supervised learning, Machine translation, OCR technology, Computer vision, Machine vision, Robotics, Intelligent Q&A, Expert systems, Neural networks, Learning algorithms, Automated reasoning, Driverless.
Blockchain Technology	Digital currency, Smart contracts, Distributed computing, Decentralization, bitcoin, Federated chains, Differential privacy technologies, Consensus mechanisms.
Cloud Computing Technology	In-memory computing, Cloud computing, Streaming computing, Graph computing, Internet of Things, Multi-party secure computing, Brain-like computing, Green computing, Cognitive computing, Converged architecture, Billion-level concurrency, EB-level storage, Information physical systems, Mobile computing, Cloud storage, Edge computing, Cloud technology.
Bigdate Technology	Big data, Data mining, Text mining, Data visualization, Heterogeneous data, Credit, Augmented reality, Mixed reality, Virtual reality, Text crawling.

Table 2
Descriptive statistics.

Variable	Variable symbol	Obs	Mean	SD	Min	Max
Digtal Transformation	Digit	1604	1.07	2.43	0.00	33.00
Number of Innovation	Num_innov	1604	24.69	46.27	0.00	527.00
Quality of Innovation	Qua_innov	1604	8.68	17.85	0.00	165.00
Firm Size	Size	1604	22.02	1.06	19.24	25.18
Firm Age	Age	1604	19.14	5.19	7.00	32.00
Debt-to-assets Ratio	Debt	1604	0.38	0.19	0.04	0.97
Roa	Roa	1604	0.05	0.08	−0.30	0.28
Largest Holder	Large	1604	0.36	0.15	0.09	0.73
Institutional Holdings	Instit	1604	0.50	0.24	0.01	0.94
Independent Director	Indep	1604	0.38	0.06	0.30	0.60
Fixed assets ratio	Fixed	1604	0.26	0.14	0.01	0.64
Concurrent Position	Concu	1604	0.28	0.45	0.00	1.00
Tobinq	Tobinq	1604	2.43	1.64	0.98	11.60
Government Subsidy	Subsidy	1604	0.01	0.02	0.00	0.15
Ownership	State	1604	0.40	0.49	0.00	1.00
Cashflow	Cash	1604	0.07	0.09	−0.22	0.31

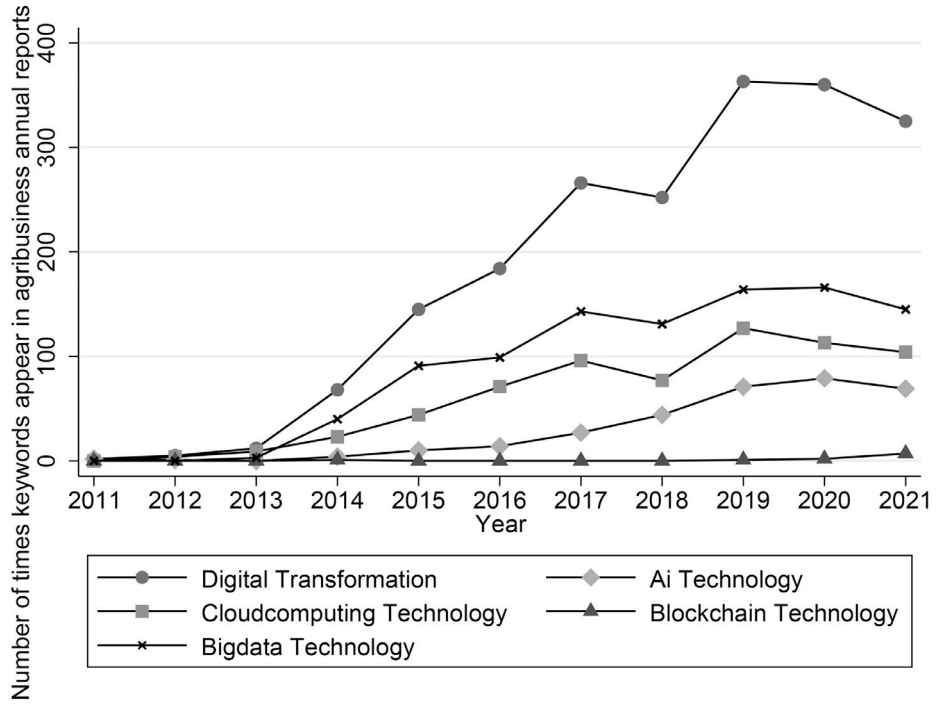

Fig. 2. Degree of digital transformation in agribusiness between 2011 and 2021.

Table 3
Descriptive statistics.

Variable	Variable symbol	Obs	Mean	SD	Min	Max
Digtal Transformation	Digit	1604	1.07	2.43	0.00	33.00
Number of Innovation	Num_innov	1604	24.69	46.27	0.00	527.00
Quality of Innovation	Qua_innov	1604	8.68	17.85	0.00	165.00
Firm Size	Size	1604	22.02	1.06	19.24	25.18
Firm Age	Age	1604	19.14	5.19	7.00	32.00
Debt-to-assets Ratio	Debt	1604	0.38	0.19	0.04	0.97
Roa	Roa	1604	0.05	0.08	−0.30	0.28
Largest Holder	Large	1604	0.36	0.15	0.09	0.73
Institutional Holdings	Instit	1604	0.50	0.24	0.01	0.94
Independent Director	Indep	1604	0.38	0.06	0.30	0.60
Fixed assets ratio	Fixed	1604	0.26	0.14	0.01	0.64
Concurrent Position	Concu	1604	0.28	0.45	0.00	1.00
Tobinq	Tobinq	1604	2.43	1.64	0.98	11.60
Government Subsidy	Subsidy	1604	0.01	0.02	0.00	0.15
Ownership	State	1604	0.40	0.49	0.00	1.00
Cashflow	Cash	1604	0.07	0.09	−0.22	0.31

proposed by the Chinese government in 2013. While artificial intelligence, cloud computing and big data are commonly adopted practices for digital transformation, blockchain-related technologies have yet to gain widespread adoption among agribusinesses. In 2021, a total of 103 agribusinesses disclosed keywords related to digital transformation in their annual reports, accounting for 42.21 % of all enterprises in that year, indicating nearly half of all agribusinesses have begun engaging in digital transformation. Among these businesses, eight had more than ten occurrences of corresponding keywords within their annual reports while most had less than five.

The basic descriptive statistics analysis of all variables in the sample agribusinesses is presented in Table 3. Among the sampled enterprises, 33.35 % are engaged in digital transformation, and each enterprise's annual report contains an average of 1.07 keywords, with a maximum occurrence of 33 times, indicating relatively low keyword density. In terms of the innovation capacity of agribusinesses, while one enterprise applied for a remarkable 527 patents in the year, there was significant variation in the number of patent applications among different agribusinesses. On average, agribusinesses filed 24.69 patents per year, out of which 8.68 were invention patents—accounting for 35.16 % of total applications. Utility model and design patents constitute most patent filings by agribusinesses; however, these patents have relatively low significance or impact, suggesting a lack of high-quality innovation within this sector.

Fig. 3 illustrates the relationship between digital transformation and innovation in agribusiness. The sample is divided into twenty groups based on the mean value of agribusiness's degree of digital transformation (arranged in ascending order), and the corresponding mean value of patent applications within each group is calculated, and finally linear fitting is performed. The positive correlation between digital transformation and the quantity and quality of innovation in agribusinesses is evident, with a stronger level of innovation observed as the degree of digital transformation increases. However, it should be noted that this analysis only establishes a certain correlation between the degree of digital transformation and agribusiness innovation, necessitating further rigorous econometric analysis to elucidate the underlying reasons and mechanisms.

Results and discussion

Baseline regression

Table 4 presents the results of the base regression of this paper. The results in column (1) indicate that digital transformation of agribusiness had a positive impact on firms' innovation output in period $t + 1$. After adding relevant control variables, the results in column (2) show that the coefficient of the firm's digital transformation variable is 0.369, which is significantly positive at the 10 % level. The above findings suggest a significant positive correlation between the extent of digital transformation and agribusinesses innovation, with each percentage point increase in enterprise digital transformation promoting approximately a 0.369 % increase in the number of patent applications. This aligns with the fundamental findings of studies such as Liu et al. (2023b) and Li et al. (2023), which suggest that digital transformation in agribusinesses can enhance their innovation capabilities. In terms of control variables, the coefficients of enterprise size, return on assets, and fixed asset ratio exhibit significant positive effects. This suggests that larger and more profitable

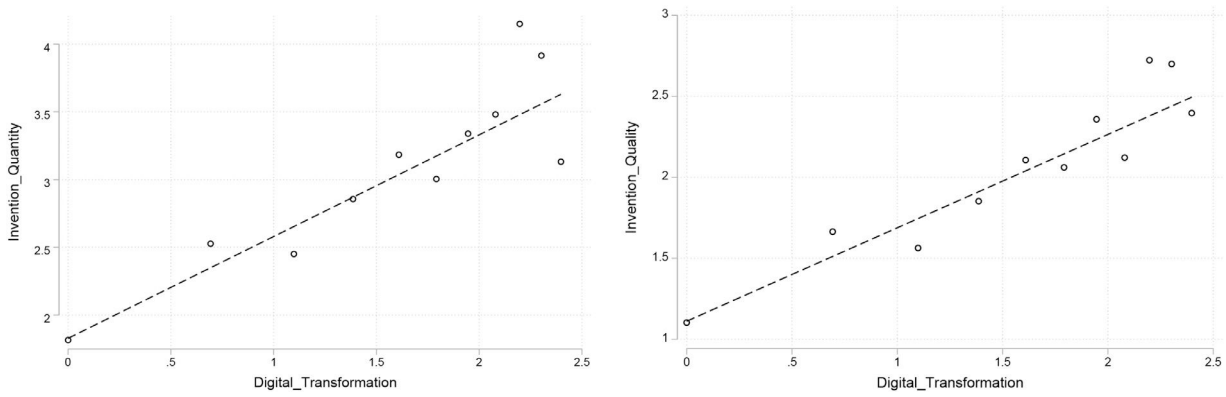

Fig. 3. The correlation between digital transformation and agribusiness innovation.

Table 4
Results of basic regression.

Variables	(1) Num_Innov	(2)	(3) Qua_Innov	(4)
L. Digtal	0.584***	0.369***	0.492***	0.310***
	(0.105)	(0.080)	(0.084)	(0.070)
L. Size		0.726***		0.559***
		(0.076)		(0.076)
L. Age		−0.024		−0.024
		(0.016)		(0.015)
L. Debt		0.050		0.137
		(0.384)		(0.333)
L. Roa		1.491**		0.745
		(0.735)		(0.630)
L. Large		−0.259		−0.635
		(0.488)		(0.416)
L. Instit		−0.350		−0.324
		(0.304)		(0.276)
L. Indep		0.553		0.255
		(0.901)		(1.003)
L. Fixed		1.072**		0.902**
		(0.448)		(0.395)
L. Concu		0.027		0.085
		(0.122)		(0.115)
L. Tobinq		0.002		−0.012
		(0.029)		(0.023)
L. Subsidy		−2.946		−1.513
		(2.073)		(1.866)
L. Cash		0.246		0.332
		(0.526)		(0.433)
L. State		0.092		0.024
		(0.142)		(0.125)
Constant	1.968***	−13.811***	1.205***	−10.596***
	(0.091)	(1.539)	(0.072)	(1.578)
Year Effect	Yes	Yes	Yes	Yes
Province Effect	Yes	Yes	Yes	Yes
Industry Effect	Yes	Yes	Yes	Yes
Obs.	1520	1408	1520	1408
R^2	0.311	0.486	0.316	0.461

Note: ***, and ** indicate statistical significance at 1 % and 5 %, respectively. The values in parentheses are robust standard errors.

agribusinesses tend to have a higher number of patent applications and stronger innovation capabilities—a finding which aligns with our initial expectations.

Given the varying complexities and intrinsic values associated with different patent types, we investigated the correlation between digital transformation and innovation quality within the agribusiness sector. The regression results presented in columns (3) and (4) of Table 4 demonstrate that the coefficient for the enterprise digital transformation variable is 0.310, which is statistically significant at the 1 % level. This suggests that digital transformation within agribusinesses plays a crucial role in promoting invention patent filings, with every 1 % increase in agribusinesses' degree of digital transformation resulting in a corresponding increase of 0.31 % more invention patents filed. The above findings suggest that digital transformation contributes to enhancing both the quantity and quality of innovation in agribusiness, thereby confirming research hypothesis 1.

Robustness test

Change explanatory variables

In the underlying regression model, we employ keyword word frequency extracted from annual reports of agricultural listed companies as a proxy variable to gauge the level of digital transformation. Companies typically provide a comprehensive overview of their business situation and development plans in the Management Discussion and Analysis (MD&A) section. Given this, we used the number of keywords within the MD&A section as a metric for assessing digital transformation. The regression results are presented in columns (1) and (2) of Table 5. The digital transformation variable significantly and positively contributes to the quality and quantity of innovation in agribusiness, with statistical significance at the 1 % level.

Replace the explained variable

In the basic regression model, we use the number of patent applications to measure the innovation level of agribusiness. In order to validate the robustness of our findings, we investigate the association between digital transformation and agribusiness innovation from the perspective of enterprise R&D investment. The regression model presented in column (3) of Table 5 indicates that digital transformation positively impacts the R&D expenditure ratio of agribusinesses, with an estimated coefficient that is statistically significant at the 1 % level. To ascertain the impact of digital transformation on enterprise innovation quality and draw upon Fang et al.'s (2018) methodology, we utilize the number of patent citations as a measure of agribusiness innovation quality. The estimated results are presented in column (4) of Table 5, where the coefficient for digital transformation is estimated to be 0.227 with a significant positive effect at the 1 % level. This suggests that a one percent increase in agribusiness' degree of digital transformation corresponds to a 0.227 % increase in patent citations. In other words, digital transformation facilitates the enhancement of innovation quality in agribusiness.

Table 5
Robustness test.

Variables	(1) Num_Innov	(2) Qua_Innov	(3) R&D	(4) Citation	(5) Num_Innov	(6) Qua_Innov
L. MDDigtal	0.336***	0.308***				
	(0.094)	(0.081)				
L. Digtal			0.002***	0.227***	0.154***	0.169***
			(0.001)	(0.064)	(0.022)	(0.030)
Constant	−14.169***	−10.857***	0.045***	−9.080***	−5.104***	−6.527***
	(1.587)	(1.606)	(0.013)	(1.321)	(0.365)	(0.500)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
lnalpha					−16.960***	−16.583***
					(0.116)	(0.355)
Obs.	1408	1408	1377	1614	1409	1409
R^2	0.478	0.454	0.386	0.406		

Note: *** indicate statistical significance at 1 %. The values in parentheses are robust standard errors.

Table 6
Robustness test.

Variables	Partial sample		Fixed effect adjustment	
	(1) Num_Innov	(2) Qua_Innov	(3) Num_Innov	(4) Qua_Innov
L. Digtal	0.442***	0.365***	0.369***	0.310***
	(0.082)	(0.070)	(0.080)	(0.070)
Constant	−13.754***	−10.850***	−13.811***	−10.596***
	(1.574)	(1.583)	(1.539)	(1.578)
Control variable	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	No	No
Province FE	Yes	Yes	No	No
Industry FE	Yes	Yes	Yes	Yes
Province*Year FE	No	No	Yes	Yes
Obs.	1213	1213	1408	1408
R^2	0.510	0.486	0.486	0.461

Note: *** indicate statistical significance at 1 %. The values in parentheses are robust standard errors.

Replace estimation method: using negative binomial regression models

Given that enterprise patent applications can only be non-negative integers, we employed the negative binomial regression model to conduct empirical tests. The results of our analysis (columns (5) and (6) in Table 5) indicate that digital transformation can promote the level of innovation in agribusinesses.

Fixed effects with more stringent controls

The Internet will be prioritized for development in cities with a higher level of economic development quality, thereby gaining a "first-mover advantage" in the application of the digital economy (Zhao et al., 2020). To account for unobservable year-to-year changes at the provincial level, we incorporated industry fixed effects, province fixed effects, and province-year interaction effects as more stringent controls. The results in columns (3) and (4) of Table 6 show that the digital transformation variables are conducive to promoting the quantity and quality of innovation in agribusinesses, and the estimated coefficients are significant at the 1 % level.

Deletion of a sample of agribusinesses with disclosure violations

Considering that the measurement of enterprise digital transformation is based on the frequency of corresponding keywords in agribusinesses' annual reports, it cannot be denied that this method is vulnerable to exaggerated publicity and may result in a situation where there is more talk than action. Therefore, we exclude agribusinesses that have been penalized for disclosure violations in order to ensure the accuracy of the core explanatory variables. The regression results are presented in columns (1) and (2) of Table 6, demonstrating the robustness of the conclusion that digital transformation can effectively enhance both the quantitative and qualitative aspects of innovation within agribusinesses.

Endogeneity issues

In the previous empirical model, we incorporated a one-period lag for variables influencing agribusiness innovation, thereby partially addressing the mutually causal relationship between digital transformation and innovation. However, the base regression model employed in this paper may suffer from omitted variable bias. Moreover, agribusinesses with stronger scientific and technological innovation are more likely to undertake digital transformation, leading to a self-selection problem. These issues can result in biased estimates when directly regressing on the base model. We therefore utilize the estimation method of instrumental variables to solve the endogeneity problems existing in the empirical model.

When choosing instrumental variables, we refer to the design ideas of Nunn and Qian (2014) and Ma and Zhu (2022). This study employs the interaction term between the logarithm of the number of telephones at the end of the year in each prefecture-level city in 1984 and the lag one-period of the Internet penetration in China as the instrumental variable, the former being related to the changes in agribusiness and the latter being related to the time variable. The development of the Internet in China was based in part on the popularity of telephone, so regions with higher telephone penetration have relatively higher Internet penetration and thus are correlated with the degree of digital transformation of agribusinesses in the region. Meanwhile, the number of telephones in different cities at the end of 1984 can be considered as an exogenous variable and does not directly affect the innovative behavior of agribusinesses.

The estimated results of IV-2SLS are reported in Table 7 (1) and (2). The number of patent applications of agribusinesses with higher degree of digital transformation is significantly higher than that of agricultural enterprises with lower degrees of digital transformation; that is, digital transformation is conducive to promoting innovation of agribusinesses. The impact of digital transformation on the quality of innovation in agribusiness is presented in columns (3) and (4) of Table 7.The estimated coefficients reveal a significantly positive effect, indicating that digital transformation has the potential to enhance the quality of innovation in agribusiness.

Mechanism analysis

Validation of mechanisms to alleviate financing constraints

Previous analysis suggests that digital transformation can help alleviate financial constraints for agribusiness in several ways (Sun, Li, Ai, & Li, 2023). First, digital transformation facilitates the reduction of operational costs for enterprises and enhances the accumulation of available capital. Second, it promotes an increase in government subsidies for agribusiness by signaling their potential to external stakeholders.

The regression results are presented in Table 8. The findings from columns (1) demonstrate that digital transformation has a significant positive impact on agribusiness government subsidies. The regression results in column (2) suggest that a higher degree of transformation is associated with a greater reduction in operating costs. Consequently, digital transformation can mitigate financing constraints. The relationship between financing constraints and firm innovation suggests that the alleviation of financing constraints can stimulate firm innovation (Hall, 1992; Brown et al., 2009; Guariglia & Liu, 2014). These findings align with our expectations, confirming Hypothesis 2.

Inspection of technology upgrading mechanism

We postulated that digital transformation can augment the R&D capability of agribusiness through two avenues: bolstering external collaborations and expanding the R&D workforce. Based on this

Table 7
Addressing endogeneity: instrumental variable estimation.

Variable	IV-2SLS			
	(1) Digtal	(2) Num_Innov	(3) Digtal	(4) Qua_Innov
L. Digtal		1.330*		1.500**
		(0.803)		(0.718)
Instrumental variable	0.107**		0.107***	
	(0.041)		(0.041)	
Constant	−3.698***	−9.847***	−3.698***	−5.419**
	(0.644)	(2.616)	(0.644)	(2.464)
Control variable	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Obs.	1409	1144	1409	1144
R^2		0.379	0.294	0.211

Note: *** indicate statistical significance at 1 %. The values in parentheses are robust standard errors.

assertion, we examined the correlation between two variables: the extent of external collaboration among enterprises (the proportion of jointly filed patents out of total patents) and the percentage of R&D personnel. The regression outcomes are presented in Table 9. The empirical findings demonstrate that digital transformation can enhance the proportion of R&D personnel in agribusinesses, though it does not contribute to external cooperation. It should be noted that an increase in external collaboration does not necessarily result in a corresponding increase in the proportion of jointly filed patents. This scenario may arise when the growth rate of jointly filed patents is smaller than that of independently filed patents. The regression results demonstrate that digital transformation has a significant positive effect on the number of jointly filed patents in agribusinesses (see column (2) of Table 9). Therefore, digital transformation facilitates technical collaboration between agribusinesses and other entities such as universities, expanding the available talent pool. These influences enhance the research and development capabilities of agribusinesses, consequently advancing innovation advancements. This analysis supports research hypothesis 3.

Heterogeneity analysis

Heterogeneity based on different digital transformation paths

Using the digital transformation indicators mentioned in the previous section, we analyzed respective relationships with agribusiness innovation to explore the impact of different types of digital development paths on such innovation. The regression results are presented in Table 10, indicating that artificial intelligence (AI), cloud computing, and big data technologies exert a significant influence on both the quantity and quality of agribusiness innovation. However, the impact of blockchain technology on agribusiness innovation remains inconclusive. This may be attributed to the limited practical application of blockchain technology in agribusiness, as evidenced by the descriptive statistical analysis presented in the previous section. In addition, the other technologies mentioned are comparatively mature. This maturity enables agribusinesses to conveniently and easily incorporate these technologies into their real production and operational processes.

Heterogeneity based on financing constraints

According to our analysis, digital transformation can help reduce the financing constraints of agribusiness and promote agribusiness innovation. Therefore, digital transformation plays a more pivotal role in fostering innovation for agribusinesses facing significant financial constraints. In this paper, agribusinesses are divided into two groups: those with weak financing constraints, and those with stronger financing constraints. The regression results show (see Column (1)-(4) in Table 11)) that both groups benefit from digital transformation, but the group with stronger constraints benefits more.

Heterogeneity based on ownership status

Based on the property rights attributes of agribusinesses, we categorize our sample agribusinesses into two groups: state-owned agribusinesses and non-state-owned agribusinesses. From the results in columns (1) to (4) of Table 12, it can be seen that digital

Table 8
Mechanism test.

Variables	(1) Subsidy	(2) Cost
L. Digtal	0.002*	−0.015*
	(0.001)	(0.008)
Constant	0.126***	0.801***
	(0.030)	(0.192)
Control variable	Yes	Yes
Year FE	Yes	Yes
Province FE	Yes	Yes
Industry FE	Yes	Yes
Obs.	1604	1604
R^2	0.302	0.686

Note: *** and * indicate statistical significance at 1 % and 10 %, respectively. The values in parentheses are robust standard errors.

Table 9
Mechanism test.

Variables	(1) Collaboration	(2) Copatent	(3) RDPerson
L. Digtal	0.021	0.271***	0.695*
	(0.013)	(0.071)	(0.368)
Constant	−0.732**	−8.697***	20.611**
	(0.307)	(1.558)	(8.304)
Control variable	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Obs.	1604	1604	1008
R^2	0.133	0.356	0.276

Note: ***, **, and * indicate statistical significance at 1 %, 5 % and 10 %, respectively. The values in parentheses are robust standard errors.

Table 10
Heterogeneity test based on digital transformation paths.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Num_Innov				Qua_Innov			
Artificial Intelligence	0.283**				0.281**			
	(0.133)				(0.117)			
Cloud Computing		0.321***				0.226**		
		(0.121)				(0.107)		
Blockchain			−0.641				−0.548	
			(0.503)				(0.569)	
Bigdate				0.353***				0.339***
				(0.101)				(0.087)
Constant	−14.443***	−14.252***	−14.693***	−14.091***	−11.092***	−11.023***	−11.337***	−10.760***
	(1.610)	(1.598)	(1.630)	(1.579)	(1.653)	(1.639)	(1.673)	(1.602)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	1408	1408	1408	1408	1408	1408	1408	1408
R^2	0.471	0.476	0.469	0.478	0.446	0.448	0.443	0.456

Note: ***, and ** indicate statistical significance at 1 %, and 5 %, respectively. The values in parentheses are robust standard error.

Table 11
Heterogeneity test based on financing constraints.

Variables	(1)	(2)	(3)	(4)
	Low-level group	High-level group	Low-level group	High-level group
	Num_Innov		Qua_Innov	
L. Digtal	0.316***	0.386***	0.252***	0.327***
	(0.089)	(0.113)	(0.078)	(0.103)
Constant	−16.140***	−13.448***	−12.279***	−10.278***
	(1.810)	(2.035)	(1.870)	(1.941)
Control variable	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Obs.	679	790	679	790
R-squared	0.529	0.538	0.517	0.496

Note: *** indicate statistical significance at 1 %. The values in parentheses are robust standard errors.

transformation significantly improves the innovation of agribusinesses in both groups, but the enhancement of state-owned agribusinesses is comparatively greater. This conclusion aligns with those of Zhuo and Chen (2023), Wang et al. (2023), and other studies. The potential explanations for this outcome are twofold: firstly, state-owned enterprises are more inclined to collaborate with universities and research institutions; secondly, state-owned enterprises tend to respond more proactively to the government's call for digital transformation and thus receive greater support from the government. This in turn facilitates the advancement of both quantity and quality of innovation within state-owned agribusinesses.

Heterogeneity based on regional disparity

China is a vast country with regional disparity in the development process. The east, for example, protects intellectual property rights more thoroughly than does the central and western regions. The east

Table 12
Heterogeneity test based on property rights attributes.

Variables	(1)	(2)	(3)	(4)
	state-owned	non state-owned	state-owned	non state-owned
	Num_Innov		Qua_Innov	
L. Digtal	0.393***	0.219**	0.249***	0.242***
	(0.110)	(0.095)	(0.083)	(0.089)
Constant	−11.456***	−16.003***	−8.101***	−12.770***
	(2.635)	(1.849)	(2.552)	(1.854)
Control variable	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Obs.	578	826	578	826
R^2	0.623	0.525	0.573	0.527

Note: ***, and ** indicate statistical significance at 1 % and 5 %, respectively. The values in parentheses are robust standard errors.

Table 13
Heterogeneity test based on regional disparity.

Variables	(1) Eastern region Num_Innov	(2) Central and Western regions	(3) Eastern region Qua_Innov	(4) Central and Western regions
L. Digtal	0.479***	0.251***	0.459***	0.130**
	(0.120)	(0.088)	(0.108)	(0.064)
Constant	−14.276***	−12.652***	−13.542***	−7.756***
	(2.249)	(2.026)	(2.464)	(1.870)
Control variable	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Obs.	700	706	700	706
R-squared	0.467	0.600	0.466	0.577

Note: ***, and ** indicate statistical significance at 1 % and 5 %, respectively. The values in parentheses are robust standard errors.

also has a more favorable policy environment for agribusiness innovation. Therefore, digital transformation may have differential impacts on the innovation behavior of agribusinesses in different regions. The results (shown in Table 13) reveal that the estimated coefficients of digital transformation on patent applications are 0.479 and 0.251 for the eastern and central/western regions respectively, both significant at the 1 % level. This suggests that digital transformation have a significantly positive promotional effect on agribusiness in both regions ,however, digital transformation plays a more prominent role in promoting agribusiness innovation within the eastern region. Further analysis regarding innovation quality also demonstrates that digital transformation has a stronger influence on enhancing innovation quality among agribusinesses located in this region.

Conclusions and policy implications

Conclusions

In China, agribusinesses serve as a crucial agent for promoting agricultural science and technology innovation. The digital economy represents the future direction of economic development, and digital transformation is recognized as a crucial pathway to promote agribusiness innovation, but this connection has yet to be fully explored. This study empirically investigates the impact and mechanism of digital transformation on agribusiness innovation using a multidimensional fixed-effects model based on data from Chinese agricultural listed companies spanning 2011 to 2021. The results show that digital transformation significantly promotes the improvement of innovation quantity and quality of agricultural enterprises. Digital transformation promotes the cooperation between agricultural enterprises and other enterprises and expands research and development personnel, thereby strengthening R&D capabilities while reducing the technological barriers that hinder innovation. Additionally, embracing digital transformation enhances the likelihood of agricultural enterprises securing government subsidies, and leveraging digital technologies effectively reduces operational costs, thus alleviating financing constraints faced by these entities. Because of the above two reasons, digital transformation plays the role of optimizing resource allocation and stimulating innovation in agricultural enterprises. Further analysis shows that three specific types of digital technologies—artificial intelligence (AI), big data analytics, and cloud computing—significantly contribute to driving agribusiness innovation. Moreover, digital transformation exerts a greater influence on innovation in state-owned agribusinesses, agribusinesses in the Eastern region and agribusinesses facing higher levels of financial constraints.

Policy suggestions

Based on these findings, we propose several policy recommendations. Firstly, policymakers should gradually steer agricultural enterprises towards digital transformation. The government should enhance investments and developments in novel infrastructures such as 5 G, industrial Internet, artificial intelligence, etc. This will expedite the establishment of an infrastructure system that empowers digital transformation and fosters the growth of the digital economy. Moreover, it is imperative for the government to actively establish a public service system for facilitating digital transformation while promoting active participation of agricultural enterprises. This entails deepening the application of digital technology to further augment operational efficiency within these enterprises. Secondly, agribusinesses should expedite the development of a proficient digital workforce. Agribusinesses should optimize their strategies for attracting digital talent; enhance the training system for nurturing skilled professionals in manufacturing industry's digital transformation; and accelerate the cultivation of a high-level, innovative, and versatile team of experts. Thirdly, agribusinesses should engage in technical cooperation. They should gradually improve the opening and sharing of resources and capabilities, strengthen external cooperation, build a mutually beneficial and cooperative ecosystem, and encourage collaborative innovations. Fourthly, financial market should get involved. The government should provide appropriate policy backing for agribusinesses engaged in digital transformation, while encouraging financial institutions to develop tailored financial service products that alleviate the financial constraints faced by traditional enterprises during their digitalization efforts. This will assist enterprises in their digital transformation journey and foster innovative development within the agricultural sector.

Research limitations and future research prospects

This paper uses agribusiness as a case study to investigate the ways digital transformation empowers innovation in traditional enterprises. The economic impact of digital transformation on enterprises is intricate and extensive, and future research will advance the study of digital transformation in agribusinesses. Firstly, efforts can be made to develop a more comprehensive measurement index based on the practical implementation of digitalization by using relevant keywords from the annual reports. Secondly, the digitalization of agricultural enterprises has a significant impact on the production and operational behavior of both upstream and downstream entities within the industrial chain. Future research can investigate the spillover effects of enterprise digital development on both upstream and downstream enterprises, as well as its impact on agricultural production.

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CRediT authorship contribution statement

Zhou Xue: Conceptualization, Formal analysis, Funding acquisition, Investigation, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Yunjie Hou:** Data curation, Visualization, Software, Formal analysis, Writing – original draft. **Guangqiao Cao:** Writing – original draft, Supervision, Formal analysis, Investigation. **Guanglin Sun:** Funding acquisition, Formal analysis, Investigation, Writing – review & editing.

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