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The Interactive Relationship Between Agricultural Enterprise Technological Innovation and Food Security: A Multidimensional Model Analysis Based on Supply Chain Management and Risk Control

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SUMMARY: *In response to the unclear two-way interaction mechanism between technological innovation and food security in agricultural enterprises, as well as the lack of empirical testing on the mediating and synergistic effects of supply chain management and risk control, this paper uses balanced panel data and agricultural enterprise data from 31 provinces in China from 2010 to 2023 as samples, and conducts empirical analysis using panel regression and structural equation modeling (SEM). The two-stage least squares method (2SLS), propensity score matching (PSM), and bias corrected bootstrap method are combined to handle endogeneity and test robustness. The research results indicate that the overall standardization effect of technological innovation on food security should reach 0.61, with a direct effect of 0.28. The indirect effects through supply chain management and risk control are 0.21 and 0.12, respectively, with indirect spillover effects accounting for over 54%; There is a significant bidirectional promotion relationship between the two, with a reverse path coefficient of 0.22 for the impact of food security on technological innovation; The interaction coefficient between supply chain management and risk control is 0.022, indicating a significant synergistic enhancement effect. The study reveals the complete mechanism of "technological innovation management optimization risk mitigation food security", which can provide theoretical support and decision-making reference for the national food security strategy.*

KEYWORDS: *Innovation Capacity; Food Security; Supply Chain Management; Structural Equation Model*

1 Introduction

According to statistics from the Food and Agriculture Organization of the United Nations (FAO), in 2022, approximately 691 million to 783 million people worldwide were suffering from hunger, accounting for 9.2% of the world's population, which is much higher than the level before the COVID-19 pandemic. To meet the growing demands of the population, the global grain output needs to increase by about 70% by 2050 compared to that in 2005. However, increasing grain production not only depends on the expansion of cultivated land but also requires the progress of agricultural science and technology to improve the per-unit yield and production efficiency. In the global food system, more than one-third of the grain output is lost and wasted due to poor management in various links of the supply chain. Countries are paying increasing attention to improving the efficiency of food supply, reducing waste, and enhancing food security through technological innovation and supply chain improvement.

As a populous country, China attaches great importance to the food security strategy. In

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recent years, China's grain output has continued to increase. In 2023, the total grain output reached 695.41 million tons, reaching a new historical high. However, the domestic demand for grain has been rising rigidly, and the degree of dependence on foreign imports has increased. From 2008 to 2020, China's grain self-sufficiency rate dropped by more than ten percentage points, and the pressure on food security has continued to increase [1]. At the policy level, the Central Committee of the Communist Party of China has clearly identified scientific and technological innovation as the fundamental way to solve the food problem, and the strategies of storing grain in the land and storing grain in technology have been elevated to national strategies. The No. 1 Central Document in 2023 emphasized the need to comprehensively consolidate the foundation of food security, strengthen the protection of cultivated land and scientific and technological support, and improve relevant safeguard mechanisms to reduce food security risks [2]. The level of agricultural scientific and technological innovation in China is relatively low. In 2020, the contribution rate of agricultural scientific and technological progress was approximately 60%, which is significantly lower than that in developed countries. This means that there is still huge potential and room to increase grain production capacity through science and technology. At the same time, the COVID-19 pandemic has exposed the vulnerability of the food supply chain. The disruptions in the global and local food supply chains have posed new challenges to food security, highlighting the necessity of innovating supply chain management to enhance resilience [3]. As an important main body of food supply, how the technological innovation of agricultural enterprises ensures food security through supply chain management and risk control has become an urgent issue to be studied.

Based on the above background, this study focuses on the interactive relationship between the technological innovation of agricultural enterprises and food security, and explores the roles and mechanisms played by supply chain management and risk control in this process. Theoretically, it enriches the research dimension of the influencing factors of food security and expands the understanding of the interaction mechanism between technological innovation and food security. Practically, it can provide decision-making references for the government to formulate agricultural science and technology policies, and for enterprises to strengthen supply chain management and risk prevention to ensure food security. This paper will conduct an empirical analysis of authoritative data and enterprise survey data in the past 10 years through the Structural Equation Model (SEM) and panel data regression [4]. The core research questions include: (1) What is the interactive relationship between the technological innovation of agricultural enterprises and food security? (2) How does supply chain management play a role in the interaction between technological innovation and food security? (3) How does risk control optimize the guarantee of food security during the technological innovation process of agricultural enterprises? (4) What role does the interaction between supply chain management and risk control play in the influence of technological innovation on food security?

Figure 1 shows the evolution trend of the development levels of agricultural technological innovation and food security in China in recent years. It can be seen that since 2008, both indices have shown an upward trend. In particular, after 2015, the agricultural technological innovation index (marked with squares) has increased rapidly, while the food security index (marked with circles) has also risen steadily but relatively gently. It can be observed that there is a positive correlation between technological progress and the food security situation, but the coordination degree between the two still needs to be improved. Peng Changsheng measured the coupling coordination degree between agricultural technological innovation and food security, and found that although the coupling degree between the two in China increased from 0.2076 to 0.3437 during the period from 2008 to 2020, it was generally in the out-of-coordination stage and a highly coordinated development had not been achieved yet [5]. Therefore, it is necessary to deeply analyze how technological innovation affects food security through multi-dimensional channels and to find ways to improve the synergistic effect.

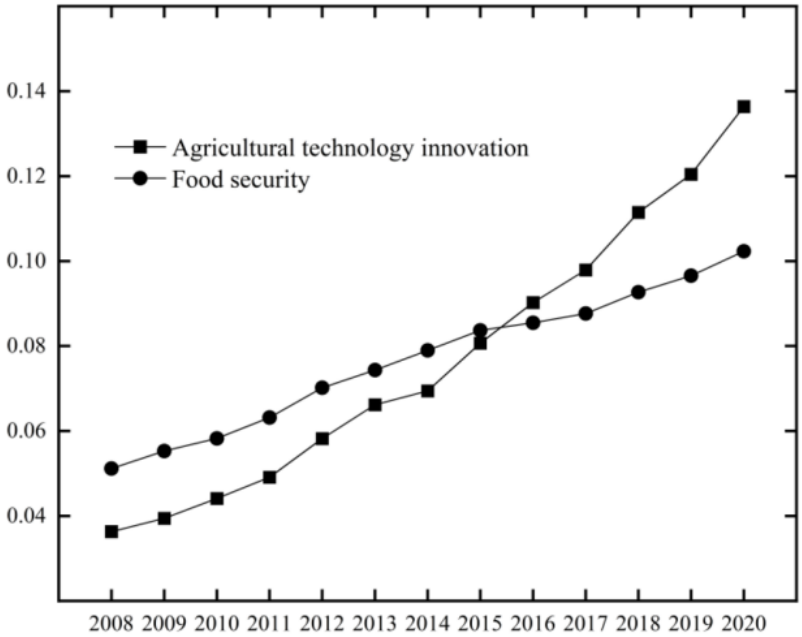

Figure 1: Trends in the Comprehensive Index of Agricultural Technology Innovation and Food Security in China from 2008 to 2020

Note: In the figure, squares and circles represent the comprehensive index of agricultural technology innovation and the comprehensive index of food security, respectively; the vertical axis shows the index value (dimensionless), and the horizontal axis indicates the year.

2 Literature Review

2.1 Theoretical Foundations of Technological Innovation in Agricultural Enterprises

Technological innovation is regarded as the fundamental driver of sustainable agricultural development and a key approach to addressing food security challenges. Technological innovation can optimize the efficiency of production factor allocation. The agricultural technology innovation system mainly includes the creation of excellent crop germplasm, the industrial application of biotechnology, the transformation and upgrading of agricultural mechanization, and the construction of digital agriculture. The above innovation paths can directly empower the improvement of grain production capacity, quality optimization, and agricultural production efficiency [6].

On the one hand, agricultural technological innovation can effectively break through the resource and environmental bottlenecks in the grain production process. Previous studies have shown that improving crop disease resistance and yield per unit area through biological breeding technology has great potential in improving grain yield and quality. Some scholars advocate that biotechnology should be used to comprehensively improve the disease resistance, yield, and quality level of major crops, while developing alternative food sources and reducing dependence on fertilizers, which can effectively alleviate the negative impact of agricultural production on the ecological environment. On the other hand, agricultural technological innovation has deeply penetrated into various aspects of grain production, processing, circulation, and consumption. Dong et al. [7] emphasized that technological progress represented by genomics has significantly accelerated the iterative upgrading process of crop varieties, ultimately promoting sustained growth in grain yield. The rise of digital technology has brought new opportunities for agricultural development. The application of digital agriculture, Internet of Things (IoT), artificial intelligence, and big data technology in the agricultural field can significantly improve the accuracy of production decisions and resource utilization efficiency. Zhang [8] emphasized that the development of agricultural IoT technology is of great significance for optimizing the efficiency of the grain production chain, reducing post-harvest losses, and ensuring supply stability.

Existing research mainly focuses on the one-way mechanism of technological innovation enhancing food security. However, there is still a relative lack of research on how food security can reverse stimulate agricultural technological innovation. Therefore, this article will shift its research focus to the two-way interaction between food security and agricultural technological innovation, forming a virtuous cycle of mutual promotion between the two. This research field still needs further exploration. Relying solely on agricultural technological innovation is difficult to completely solve the various challenges faced by food security. Incorporating supply chain management and risk control into the research and analysis framework, and systematically exploring the multidimensional mechanisms that support food security, has important theoretical value and practical significance.

2.2 Advances in Food Security Research

The Food and Agriculture Organization of the United Nations (FAO) conceptualizes food security from four dimensions: availability, accessibility, utilization, and stability. Among them, availability focuses on the production and supply of food, accessibility is related to the distribution efficiency of food and residents' purchasing power, utilization emphasizes food nutrition absorption and food safety guarantee, and stability focuses on the continuity and risk resistance of long-term food supply. In the context of the global supply chain disorder caused by the intensification of global climate change and the COVID-19, food security related research has increasingly highlighted the concern for supply chain resilience and systemic risks. Related research has evaluated the security mechanism for vulnerable groups under the impact of food supply and demand, and advocated the construction of a food security social safety net to enhance the food access capacity of vulnerable groups.

Domestic scholars' research mainly focuses on grain production capacity, protection of arable land resources, fluctuations in grain prices, and the impact of grain related policies on national food security. For example, Liu Huiyu used a coupled model to systematically explore the interactive relationship between food security and agricultural ecological protection [9]. It can be seen that research on food security has gradually shifted from a narrow yield-oriented approach in the early days to a more comprehensive system perspective, emphasizing the use of comprehensive strategies to ensure the stability of food supply. As stated in the 14th Five Year Plan for National Economic and Social Development of the People's Republic of China and the Long-Range Objectives for 2035, technological innovation is the fundamental path to solving the challenges of food security. It is urgent to incorporate technological innovation into the research framework of food security and explore its mechanism of action in depth.

2.3 The Role of Supply Chain Management and Risk Control in Agricultural Enterprises

The full chain supply chain management from production to consumption plays a crucial role in ensuring food security. The agricultural supply chain covers key links such as production, harvesting, storage, transportation, processing, and distribution, all of which will have a significant impact on the final food supply. About one-third of the world's food is lost or wasted during harvesting, processing, and circulation, directly reflecting the inefficiency caused by poor supply chain management. Strengthening supply chain management, reducing food losses, and improving circulation efficiency have been widely regarded as important paths to ensure food security. The optimization of cold chain logistics and storage technology can minimize the spoilage and loss of grain during transportation and storage, while the informatization and visualization management of the supply chain can help achieve timely allocation of resources and alleviate regional food supply and demand imbalances. In recent years, the application of digital technology in agricultural supply chains has become a hot topic in academic research. Among them, blockchain technology can significantly enhance the traceability and transparency of the supply chain, while artificial intelligence technology can optimize inventory management and distribution route planning, which helps to further improve the responsiveness and resilience of the supply chain, thereby ensuring the accessibility and stable supply of food.

Under the emergency situation, the internal relationship between supply chain management and food security has become increasingly prominent. For example, during the COVID-19, the global and regional logistics systems were severely impacted, and food supply shortages occurred in some regions. Tao Yaping pointed out that strengthening the risk management and control capability of the agricultural supply chain is an important support to ensure the implementation of the strategic goal of food security [10]. Scholars such as Wang Liangliang believe that accurate identification and scientific assessment of various risks in the supply chain are necessary prerequisites for maintaining food security. Therefore, building a resilient food supply chain system has become a core strategic measure to ensure national food security in the new era.

On the other hand, due to the multidimensional risk constraints faced by agricultural production and the food supply chain system, risk control is also an indispensable part of agricultural enterprises to maintain food security. These risk constraints mainly include natural disasters such as drought, floods, and pests, market fluctuations such as lower grain prices and supply-demand imbalances, as well as policy adjustments and changes in the international geopolitical environment [11]. If not effectively mitigated, it will offset the yield increasing benefits brought by technological empowerment, and in severe cases, even trigger systemic crises in food supply. Improving efficient risk control mechanisms is the core support for stable operation of food security. In the context of the digital economy, we should rely on big data technology to empower the agricultural supply chain, enhance the scientific level of risk decision-making, and refine safety management [12]. The agricultural supply chain is a key support system for ensuring food security and promoting rural economic development. It has significant vulnerability to natural disasters and market fluctuations, so it is urgent to establish a systematic risk management system, including risk monitoring and early warning, diversified supply chain layout, application of agricultural insurance and futures tools, and construction of emergency response plans. Scholars from Tsinghua University have pointed out that improving supply stability, strengthening production resilience, consolidating sustainable production capacity, maintaining policy continuity, and promoting domestic and international market synergy are effective paths to enhance food security resilience and risk management capabilities. Therefore, the level of agricultural production technology and supply chain management capabilities are the core elements that determine food security resilience and risk control effectiveness [13]. Integrating supply chain optimization and risk control deeply into the food security guarantee system can significantly improve the comprehensive food security guarantee capability of the country.

Agricultural technological innovation can significantly improve the efficiency of food production and supply, but its application effectiveness highly depends on a sound supply chain management system and robust risk control mechanisms, because supply chain management can further amplify the positive empowering effect of agricultural technology on food security by reducing food circulation losses and improving circulation efficiency; As a "protective barrier" for food security, risk control can still ensure the stability of food supply even in the event of adverse events. At present, there is still a lack of research on systematically testing the synergistic impact of agricultural technology innovation, supply chain management, and risk control on food security.

3 Theoretical Analysis and Research Hypotheses

3.1 Theoretical Analysis

The Resource Based View (RBV) holds that technological innovation is the core resource of enterprises. This study systematically analyzes the dimensions of the technological innovation capability of agricultural technology enterprises through empirical investigations. The research results indicate that technological research and development capabilities and marketing capabilities are the core key resources for agricultural enterprises' technological innovation, which can significantly enhance the comprehensive competitiveness and business performance of agricultural enterprises [14], and verify the view that internal innovation resources (especially technological capabilities) are the core support for agricultural enterprises to obtain sustainable competitive advantages.

Transaction Cost Economics (TCE) suggests that reducing transaction costs optimizes agricultural supply chains. Based on survey data from farmers in Northeast China, Xue Y employed a multivariate Probit model to empirically analyze the impact of transaction costs on the stability of agricultural production service contracts. The study found that excessively high information search and contract fulfillment costs significantly weaken farmers' willingness to engage in long-term cooperation with service providers. Conversely, institutional arrangements that lower farmers' transaction costs can enhance their willingness to continue cooperation and improve the efficiency of upstream and downstream linkages in agricultural supply chains. To mitigate cooperation risks arising from transaction costs, it is recommended that governments provide supervision and incentives to reduce transaction barriers in farmers' access to agricultural services, thereby fostering closer connections between smallholder farmers and agricultural service providers and optimizing supply chain management efficiency [15]. In other words, controlling and reducing transaction costs can improve coordination in grain production and distribution, contributing to stable grain supply.

Supply Chain Management Theory explains that supply chain integration enhances grain circulation efficiency and security. Using panel data from 31 Chinese provinces from 2011 to 2021, Chang J constructed an econometric model to analyze the resilience of grain supply chains under the conditions of the digital economy. The traditional grain supply chain has problems such as low circulation efficiency and weak coordination and linkage among various links. It is highly susceptible to supply interruption shocks in emergency situations. It is urgent to introduce modern supply chain management concepts such as digital supply chain to achieve efficient information exchange and flow between the production and distribution ends, thus building a low-cost and high-efficiency grain circulation system, while significantly reducing supply chain uncertainty and bullwhip effect risks. It can be seen that relying on supply chain management theory to optimize the grain supply chain system, through strengthening information sharing, deepening segmented collaboration and other paths, can effectively improve the efficiency of grain circulation.

Under the framework of risk management theory, agricultural insurance is an important support tool for stabilizing food supply and a core policy tool for the country to support the development of agriculture, rural areas, and farmers. It has unique advantages in reducing agricultural production risks and stabilizing food production and supply. Agricultural insurance, as a key risk management measure, can provide farmers with corresponding economic compensation in the event of natural disasters or market fluctuations, thereby ensuring the continuity of food supply. This further confirms the applicability of risk management theory in the agricultural field and can effectively improve the level of food security.

3.2 Research Hypotheses

Based on existing literature review, this article constructs a theoretical analysis framework that integrates technological innovation, supply chain management, risk control, and food safety. The logical sequence is as follows: agricultural enterprise technological innovation can strengthen the material foundation of food security by improving grain production and production efficiency. This process relies on the support of efficient supply chain management to achieve smooth flow of grain from the production end to the consumption end. Risk control can effectively alleviate uncertainty in the production and circulation process, ultimately jointly ensuring the level of food security. Based on the above theoretical framework, this article proposes the following research hypotheses:

Hypothesis 1A (Technological Innovation → Food Security):

Agricultural technological innovation has a significant improvement effect on food security level. For example, Gao Shuang conducted empirical tests based on panel data from 65 countries from 2001 to 2021, and the results showed that activating the technological innovation vitality of the seed industry can effectively improve a country's food security level, revealing that the technological innovation capability of agricultural enterprises has a positive driving effect on food security [16].

Hypothesis 1B (Food Security → Technological Innovation):

As an important foundation for sustainable agricultural development, the improvement of food security level will also stimulate agricultural enterprises to increase investment in technological innovation, effectively ensure stable supply of agricultural products, and create favorable conditions for enterprises and governments to optimize resource allocation and increase research and development investment. Strengthening the grain production capacity and technological support system can help promote the formation of a virtuous cycle between food security and technological progress [17]. For example, Hu Feifan et al. (2025) proposed that technological innovation and its promotion and application should be embedded in the food supply chain security strategy system to comprehensively enhance food security guarantee capabilities. Higher levels of food security will significantly enhance the attention and investment of various sectors of society in agricultural innovation, thereby effectively driving agricultural enterprises to carry out technological research and innovation practices.

Hypothesis 2 (Mediating Role of Supply Chain Management):

The agricultural supply chain covers key links such as harvesting, warehousing, transportation, processing, and distribution. An efficient food supply chain can effectively transform technological innovation driven yield growth into stable and accessible food supply [18]. Inefficient operation in any link may lead to food loss and waste. A sound supply chain management system can optimize the configuration of logistics and warehousing links, reduce post production losses, and improve circulation efficiency. Therefore, enhancing the resilience and operational efficiency of the grain supply chain is the core measure to ensure stable grain supply. At the same time, technological innovation in the warehousing and transportation fields can significantly reduce grain losses in production, warehousing, and transportation links. From this, it can be seen that the effect of technological innovation on food security depends on the intermediary transmission effect of supply chain management. Efficient supply chains further amplify the positive empowering effect of technological innovation by improving terminal supply efficiency. Hypothesis H2 is proposed based on this: Supply chain management plays a moderating effect between technological innovation and food security.

Assumption 3: The mediating role of risk control. Agricultural enterprises generally face multiple uncertainties such as climate disasters and market fluctuations in the process of technological innovation and production and operation. It is urgent to adopt systematic risk control measures to effectively disperse and mitigate the external shocks mentioned above, avoid the loss of technological innovation results due to sudden risks, and stabilize the level of food security guarantee. Hypothesis H3 is proposed based on this: Risk control plays a mediating role in the path of technological innovation affecting food security, thereby ensuring the stable achievement of food security goals.

Assumption 4: The interactive effect of supply chain management and risk control. A sound supply chain management and risk control system can form significant synergistic benefits. On the one hand, an efficient supply chain can enhance the risk resistance ability of agricultural enterprises, and diversified circulation channels and refined inventory management can effectively alleviate the risk of local market disruptions; On the other hand, a risk control mechanism centered on agricultural insurance and risk warning can ensure the stable operation of the entire supply chain and avoid disruptions in grain production and distribution caused by unexpected events. The synergistic effect of the two helps to more efficiently retain, allocate, and supply the grain production benefits brought by technological innovation, thereby maximizing the level of food security. Based on the above collaborative mechanism, this article proposes hypothesis H4: the interaction term between supply chain management and risk control plays a positive moderating role in the relationship between technological innovation and food security, and the improvement effect of technological innovation on food security is more significant.

4 Research Analysis

4.1 Research Methodology

This article adopts a quantitative research paradigm and selects panel data regression and structural equation modeling (SEM) for empirical analysis: (1) Using panel regression models to test the direct impact of technological innovation, supply chain management, and risk control on food security, and controlling for the lag effect of food security in the model; (2) Using structural equation modeling to identify the indirect transmission path of technological innovation on food security through supply chain management and risk control; (3) Further investigate the reverse driving effect of food security on technological innovation.

4.2 Data Collection and Description

4.2.1 Data Sources

The macro data in this article is taken from official public databases such as the National Bureau of Statistics, the Ministry of Agriculture and Rural Affairs, the Food and Agriculture Organization of the United Nations (FAO), and the World Bank. The indicators cover China's agricultural technology investment, grain production, supply chain management level, and agricultural insurance coverage from 2010 to 2023. The micro data of enterprises are screened based on the following criteria: samples that do not involve agriculture, forestry, animal husbandry, and fisheries in their main business and enterprises with missing key data are excluded, and the final effective sample size N=67 is determined. Micro level data is obtained through research on agricultural enterprises, including variables such as annual R&D investment and supply chain digitalization level; Meanwhile, this article compiles the annual reports and industry research reports of leading agricultural enterprises in the industry to depict their levels of technological innovation, supply chain management, and risk control [19].

4.2.2 Descriptive Statistical Analysis

The statistical results show that since 2010, China's overall grain production has maintained steady growth [20]. The total grain production in the country has increased from about 546 million tons in 2010 to 695 million tons in 2023, and the per capita grain possession has remained above 470 kilograms, which is at a historically high level. The average R&D investment intensity of sample agricultural enterprises has increased from 2% in 2010 to over 5% in 2023. Supply chain efficiency indicators such as inventory turnover days have been significantly optimized, and the coverage of agricultural insurance continues to expand. Currently, China's agricultural insurance premium scale has ranked first in the world. The above results indicate that the improvement of technological innovation capability, optimization of supply chain management, and improvement of risk control level are significantly synchronized with the sustained improvement of food security.

4.3 Variable Definitions and Measurements

Technological Innovation (TI): It comprehensively measures the R&D intensity of enterprises (the proportion of R&D expenditure to operating income), the number of agricultural related patent authorizations, and the conversion rate of technological achievements.

Supply Chain Management (SCM): Using inventory turnover, logistics distribution efficiency, and cold chain coverage as proxy indicators to reflect the operational efficiency and supply reliability of the food supply chain.

Risk Control (RC): Measuring the coverage of agricultural insurance and the adequacy of grain reserves, it reflects the ability of enterprises to resist agricultural production risks and market fluctuations.

Food Security (FS): Measured by grain yield growth rate, per capita grain availability, and stock-to-consumption ratio (i.e., the grain inventory-to-consumption ratio) to evaluate food security levels.

4.4 Measurement Models

4.4.1 Panel Data Regression Model

To quantitatively examine the impact of technological innovation, supply chain management, and risk control on food security, the following dynamic panel regression model is constructed:

$$\mathrm{FS}_{\mathrm{it}} = \alpha + \beta_1 \mathrm{TI}_{\mathrm{it}} + \beta_2 \mathrm{SCM}_{\mathrm{it}} + \beta_3 \mathrm{RC}_{\mathrm{it}} + \beta_4 \mathrm{FS}_{\mathrm{i,t-1}} + \gamma \mathrm{X}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{1}$$

4.4.2 Structural Equation Model (SEM) Analysis

To further explore how technological innovation affects food security through mediating pathways such as supply chain management and risk control, this paper constructs a Structural Equation Model (SEM). SEM can simultaneously estimate multiple causal pathways and treats technological innovation, supply chain management, risk control, and food security as latent variables, measured by their respective observed indicators. This approach enables the assessment of both the direct impact of technological innovation on food security and its indirect effects through SCM and RC. As shown in Table 1.

Table 1: Variables and their measurement indicators

Variable name	Indicator measurement
Technological Innovation (TI)	Enterprise R&D investment intensity, number of agriculture-related patents, and rate of transformation of scientific and technological achievements
Supply chain management (SCM)	Inventory turnover rate, logistics distribution efficiency, cold chain coverage rate
Risk control (RC)	Agricultural insurance coverage rate, grain reserve adequacy rate
Food security (FS)	Grain yield growth rate, per capita grain availability, stock-to-consumption ratio

Consists of two parts: the measurement model and the structural model. (1) The measurement model defines the relationship between latent variables and observed indicators. TI (Technological Innovation) is a latent factor reflected by two observed indicators: R&D investment and number of patents; SCM (Supply Chain Management) is reflected by inventory turnover rate and cold chain investment; RC (Risk Control) is reflected by insurance coverage rate; FS (Food Security) is reflected by total grain output and per capita availability. Through confirmatory factor analysis (CFA), the indicator factor loadings of all latent variables reached significant levels, with composite reliability and average variance extracted meeting threshold requirements, indicating good convergent validity and reliability of the scale [21]. (2) The structural model establishes the path relationships among latent variables. Based on research hypotheses, technological innovation has both a direct path to food security and indirect paths through supply chain management and risk control, while food security in turn has a reverse path to technological innovation. Therefore, the structural model contains five main causal paths: TI → FS (direct effect), TI → SCM → FS (mediation effect via supply chain), TI → RC → FS (mediation effect via risk control), FS → TI (reverse path of food security to technological innovation), and TI → (RC×SCM) → FS (indirect path of TI through the interaction effect of supply chain management and risk control). Model parameters were estimated using the maximum likelihood method, and model fit was evaluated through appropriate goodness-of-fit indices. In structural equation modeling, the core focus is on the size and practical significance of each path coefficient, as well as whether the indirect impact of technological innovation on food security through mediating variables is statistically significant. Based on this, this study calculated the deviation corrected Bootstrap confidence interval and validated the significance of indirect paths using Sobel test. The results show that if the indirect effect is significant and accounts for a large proportion of the total effect, supply chain management and risk control play an important mediating role in the technology driven process of improving food security.

4.5 Robustness Test

In response to the potential endogeneity issues in R&D investment, this article uses the instrumental variable method (IV) for estimation, selects exogenous instrumental variables to perform instrumental variable regression on the core explanatory variables, and selects government research subsidy intensity and regional research institution density as alternative instrumental variables for technological innovation; The above variables are not directly related to the grain output of enterprises, and can have a significant positive impact on the R&D

investment of enterprises, meeting the requirements of exogeneity and correlation of instrumental variables.

This article further uses propensity score matching (PSM) for empirical testing, setting companies with high levels of technological innovation investment as the treatment group and companies with low levels of technological innovation investment as the control group. Sample matching is conducted based on two characteristic variables: company size and property rights, to construct a comparable empirical analysis sample.

To verify the robustness of the research findings, this study conducted a robustness test using replacement variables. Regression analysis was conducted by reconstructing the core variable measurement method, including replacing the number of patent applications with the number of authorized patents, replacing the R&D investment revenue ratio with the proportion of technical personnel, and replacing inventory turnover with the number of days in the warehouse week (negatively correlated with inventory turnover).

5 Empirical Analysis

5.1 Panel Data Regression Analysis

This article selects balanced panel data from 31 provinces in China from 2010 to 2023, which are sourced from the National Bureau of Statistics, the Ministry of Agriculture and Rural Affairs, the CARD China Agricultural Enterprise Research Database of Zhejiang University, and public annual reports of agricultural listed companies. Based on this, empirical quantitative analysis is conducted on the driving factors of food security.

The dependent variable of food security (FS) was measured using the provincial annual total grain output (10000 tons). The results showed that China's comprehensive grain production capacity steadily improved during the sample period, with the total grain output exceeding 550 million tons for the first time in 2010, climbing to 660 million tons in 2015, and maintaining a stable level of over 650 million tons for several years thereafter; In 2018, the total grain production was close to 660 million tons, and the per capita grain possession during the same period was about 470 kilograms, higher than the global average grain supply level.

The core explanatory variable technological innovation (TI) is measured using dual indicators of agricultural enterprise R&D investment and agricultural patent quantity, where R&D investment is measured by the proportion of provincial agricultural R&D expenditure to regional gross domestic product (GDP); The number of patents is calculated based on the annual number of agricultural patent applications accepted. The test results show that since the 2010s, China's investment in agricultural technology innovation has shown a rapid growth trend, with the scale of public agricultural research and development funds surging from 1.3 billion US dollars in 2000 to 6.6 billion US dollars in 2019, an increase of about five times; The number of agricultural patent applications has risen from 1845 in 1995 to 108711 in 2018.

The mediating variable supply chain management (SCM) measures inventory turnover and cold chain logistics investment through two dimensions: (1) inventory turnover is calculated based on the average inventory turnover frequency of agricultural listed companies; (2) Cold chain logistics investment adopts provincial agricultural product cold storage capacity or cold chain logistics market size as proxy indicators. The results show that the modernization process of China's agricultural supply chain has significantly accelerated, and the efficiency and stability of the agricultural supply chain continue to be optimized. Among them, the cold chain logistics market maintains a double-digit annual growth rate, and the market size has grown from about 80 billion yuan in 2010 to nearly 400 billion yuan in 2020. It is expected to exceed 500 billion yuan in 2023.

The intermediary variable risk control (RC) uses agricultural insurance coverage as a proxy indicator, and the results show that the risk protection capacity of agricultural production continues to strengthen. Since China promoted the full implementation of agricultural insurance through policy guidance in 2007, this field has achieved rapid development. In 2015, the national agricultural insurance coverage rate was only about 18%, which has increased to 24% by 2020 and is expected to further climb to 40% by 2030.

Control Variables: Regional economic development level and farmer income, measured by per capita GDP (constant prices) and rural residents' per capita disposable income (yuan), respectively. Both are expected to have a positive impact on grain output.

Model 1 (testing Hypothesis 1A) is a fixed-effects model with food security as the dependent variable and technological innovation as the independent variable:

$$\mathrm{FS}_{\mathrm{it}} = \alpha_1 + \beta_1 \mathrm{TI}_{\mathrm{it}} + \gamma \mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}} + \varepsilon_{\mathrm{it}} \tag{2}$$

where μi represents firm fixed effects, Xit denotes control variables, and β1 is expected to be positive, indicating that greater investment in technological innovation leads to higher levels of food security.

Model 2 (testing Hypothesis 1B) takes technological innovation as the dependent variable and food security as the independent variable:

$$\mathrm{TI}_{\mathrm{it}} = \alpha_2 + \beta_2 \mathrm{FS}_{\mathrm{it}} + \gamma' \mathrm{X}_{\mathrm{it}} + \upsilon_{\mathrm{i}} + \eta_{\mathrm{it}} \tag{3}$$

Examining the reverse promoting effect of food security on technological innovation, β2 is expected to be positive, indicating that an improvement in food security levels will stimulate enterprises to increase investment in technological innovation (for example, increased grain production generates revenue, which in turn feeds back into R&D).

Model 3 (Mediation Effect Model) adds two mediating variables, supply chain management and risk control, on the basis of Model 1:

$$\mathrm{FS}_{\mathrm{it}} = \alpha_3 + \beta_3 \mathrm{TI}_{\mathrm{it}} + \beta_4 \mathrm{SCM}_{\mathrm{it}} + \beta_5 \mathrm{RC}_{\mathrm{it}} + \gamma'' \mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}} + \varepsilon'_{\mathrm{it}} \tag{4}$$

Testing Hypothesis 2 and Hypothesis 3: Technological innovation indirectly enhances food security by improving supply chain management efficiency and risk control levels. It is expected that β3 will decrease compared to Model 1 after adding the mediators, while β4 and β5 will be significantly positive, indicating the presence of partial mediation effects.

Model 4 (Interaction Model): Building upon Model 3, this model incorporates the interaction term between supply chain management and risk control:

$$\mathrm{FS}_{\mathrm{it}} = \alpha_4 + \beta_6 \mathrm{TI}_{\mathrm{it}} + \beta_7 \mathrm{SCM}_{\mathrm{it}} + \beta_8 \mathrm{RC}_{\mathrm{it}} + \beta_9 (\mathrm{SCM}_{\mathrm{it}} \times \mathrm{RC}_{\mathrm{it}}) + \gamma''' \mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}} + \varepsilon''_{\mathrm{it}} \tag{5}$$

Testing Hypothesis 4: The interaction term β9 is expected to be significantly positive, indicating that the promoting effect of technological innovation on food security is stronger when both supply chain management and risk control reach high levels simultaneously.

Model estimation method: Panel data adopts either a fixed-effects or random-effects model. First, the Hausman test is used to select the appropriate model form; if the Hausman test is significant ($p < 0.05$), the fixed-effects model is preferred to control for unobserved individual effects on the regression. Year dummy variables in the model are employed to control for annual macroeconomic shocks. All continuous variables have undergone appropriate data smoothing processing (such as natural logarithmic transformation) to effectively reduce estimation bias caused by model heteroscedasticity. To further enhance the reliability of empirical results, robust standard errors are used in the regression analysis process to correct for the interference of sequence correlation and heteroscedasticity on the estimation results, ensuring the consistency and effectiveness of regression coefficient estimation.

Regression result preview: The following report reports the core regression coefficients (standard error in parentheses) and significance level markers, where * represents $p<0.05$ (significant) and * * represents $p<0.01$ (highly significant).

According to Table 2, (1) in Model 1, the regression coefficient of technological innovation on food security is 0.152, which is significant at the 1% statistical level ($p<0.01$), indicating that technological innovation activities such as research and development investment can significantly improve the level of food security. (2) In Model 2, the coefficient of the impact of food security on technological innovation is 0.130, which is also significant at the 1% level ($p<0.01$), indicating that the improvement of food security level will reverse the incentive for enterprises to increase technology research and development investment. (3) In Model 3, the regression coefficient of technological innovation decreased from 0.152 to 0.098, but still maintained statistical significance, indicating that there is a partial mediating effect of technological innovation on food security. (4) The regression coefficients of supply chain management and risk control are both positive and significant, indicating that technological innovation can indirectly promote the improvement of food security level through two paths: improving supply chain efficiency and alleviating agricultural production risks. (5) In Model 4, the regression coefficient of the interaction term (supply chain x risk) between supply chain management and risk control is 0.022, which is significant at the 1% level ($p<0.01$), indicating that when the supply chain management capability and risk control level are both at a high level, the promoting effect of technological innovation on food security will be further strengthened.

Table 2: Regression analysis results of panel data

variable	Food security (MODEL1)	Technological innovation (MODEL2)	Food security (MODEL3)	Food security (MODEL4)
Investment in technological innovation	0.152**	-	0.098**	0.084**
Grain safety output	-	0.130**	-	-
Inventory turnover rate	-	-	0.087**	0.075**
Agricultural insurance coverage rate (RC)	-	-	0.065**	0.054**
Supply chain × risk (interaction term)	-	-	-	0.022**
Control variable 1 (enterprise scale)	0.011	0.008	0.005	0.006
Control variable 2 (asset-liability ratio)	-0.003	-0.002	-0.001	-0.001
Constant term	5.321**	-0.214	3.876**	3.801**
Individual & Year Effects	There is	There is	There is	There is
R^2 (adjusted)	0.35	0.27	0.42	0.45

5.2 Structural Equation Modeling (SEM) Analysis

To further identify the indirect impact mechanism of technological innovation on food security through supply chain management and risk control, as well as the reverse driving effect of food security on technological innovation, this paper constructs a structural equation model (SEM) to conduct mechanism testing. The model assumes that technological innovation not only directly promotes food security, but also indirectly improves the level of food security through the individual mediating effects of supply chain management and risk control, as well as the interactive linkage effects between the two. At the same time, the reverse feedback path from food security to technological innovation is considered, meaning that higher food security levels promote greater investment in technological innovation, forming a virtuous cycle. The model path hypotheses are as follows: TI → FS (direct path); FS → TI (reverse path of food security on technological innovation); TI → SCM → FS (indirect path of TI via supply chain management); TI → RC → FS (indirect path of TI via risk control); TI → (RC×SCM) → FS (indirect path of TI via the interaction of supply chain management and risk control).

In SEM mediation analysis, the following testing steps are generally included.

1. Examine whether the direct effect of the independent variable (X: TI) on the dependent variable (Y: FS) is significant. If X→Y is not significant, it is common to further consider whether issues such as model specification or measurement lead to the insignificance, but this does not necessarily directly negate mediation.

2. Test whether the effect of X on the mediating variables (M: SCM, RC) is significant. If X→M is not significant, it indicates that X does not function through M; if significant, proceed to the next step.

3. Test whether the effect of the mediating variable (M) on the dependent variable (Y) is significant (while controlling for X). If M→Y is significant, it indicates that M indeed affects Y.

4. Compare the coefficient changes of X on Y when M is included or excluded: If after controlling for M, the coefficient of X on Y changes from significant to insignificant (or the significance is significantly reduced), and M has a significant effect on Y, then it indicates complete or partial mediation. If X still has a significant effect on Y but the coefficient decreases, it suggests partial mediation.

5. Bootstrap/Sobel Test: In modern mediation analysis, the Bootstrap or Sobel test is commonly employed to assess whether the indirect effect is significant [22]. The Bootstrap method has been proven to have better robustness and reliability in large sample scenarios or when the model does not strictly satisfy the normality assumption.

The structural equation model (SEM) mentioned above includes one direct effect path, three parallel mediation effect paths, and one feedback effect path. Considering that the intermediary variables supply chain management (SCM) and risk control (RC) are both continuous indicators, and assuming that the model error term follows a normal distribution, this paper adopts a combination of two-stage least squares (2SLS) and maximum likelihood estimation (ML) to estimate the parameters of the structural equation model. The results showed that all fitting indicators reached the ideal level ($\chi^2/df=2.05$, CFI=0.97, RMSEA=0.04), and all path coefficients passed statistical significance tests, indicating that the model setting was reasonable and the fitting effect was good. Table 3 shows that technological innovation (TI) not only has a direct promoting effect on food security (FS), but also has a significant indirect positive impact on food security through two intermediary paths: supply chain management and risk control [23].

This study used the bias correction Bootstrap method to calculate the estimated indirect effects and their confidence intervals through 5000 repeated samples. The results of the mediation effect decomposition are shown in Table 4. Direct effect (TI → FS): The direct path coefficient of technological innovation on food security is 0.28, and it is significant at the 1% statistical level ($p<0.01$). After controlling for other influencing factors, technological innovation itself has a significant positive effect on increasing grain production and ensuring food supply security; Even without considering the intermediary transmission channels of supply chain management and risk control, agricultural technological progress can directly promote the improvement of agricultural production efficiency and grain yield.

Table 3: Standardization coefficients for each path

Path	Standardized path coefficient	Significance
TI → FS (Direct action)	0.28	p<0.01
TI → SCM (In Indirect pathway1)	0.55	p<0.01
SCM → FS (In Indirect pathway1)	0.38	p<0.05
TI → RC (In Indirect pathway2)	0.47	p<0.01
RC → FS (In Indirect pathway2)	0.26	p<0.05
FS → TI (Reverse path)	0.22	p<0.05
TI → (RC×SCM) → FS	0.30	p<0.01

Table 4: Decomposition results of mediation effect

Intermediary pathway	Intermediary pathway	95% Bootstrap confidence interval	Significance
TI→SCM→FS	0.21	[0.13,0.30]	p<0.05
TI→RC→FS	0.12	[0.06,0.20]	p<0.05
TI→(SCM×RC)→FS	0.19	[0.10,0.27]	p<0.01

Indirect Effect I (TI → SCM → FS): The indirect transmission path of technological innovation affecting food security through supply chain management can be broken down into two chain relationships. Among them, the path coefficient of technological innovation on supply chain management is 0.55 ($p<0.01$), and the path coefficient of supply chain management on food security is 0.38 ($p<0.05$). The estimated value of indirect effect I can be obtained by multiplying the two path coefficients: $0.55 \times 0.38 \approx 0.21$. The new technologies and modern management models generated by technological innovation include intelligent inventory control, full traceability of cold chain, etc., effectively reducing post harvest and circulation losses of grain and improving the efficiency of agricultural product distribution and operation. The spillover effect has high statistical significance, with indirect effect I accounting for 43% (0.21/(0.21+0.28)) of the total effect of technological innovation, fully demonstrating the contribution of technological innovation to food security.

Indirect Effect II (TI → RC → FS): The path coefficient of technological innovation on risk control is 0.47 ($p<0.01$), indicating that technological innovation can effectively improve the level of agricultural risk management. This is reflected in promoting the development of weather index insurance products and strengthening risk monitoring and prevention practices through big data technology. The path coefficient of risk control on food security is 0.26 ($p<0.05$), indicating that the improvement of risk guarantee level can significantly promote food security, confirming that improving the risk sharing mechanism can effectively stabilize food production and ensure food security. The estimated value of indirect effect II can be obtained by multiplying the coefficients of two paths: $0.47 \times 0.26 \approx 0.12$. This indirect effect accounts for about 18% of the total effect of technological innovation (0.12/(0.21+0.12+0.28)). The impact of this indirect effect is relatively small, but it still plays an important supporting role in promoting food security through technological innovation.

The total effect (standardization coefficient) of technological innovation on food security, taking into account both direct and indirect effects, is calculated as follows: $0.28+0.21+0.12 \approx 0.61$, indicating that for every one standard deviation increase in technological innovation level, the food security level will correspondingly increase by about 0.61 standard deviations. Further analysis of the effect composition reveals that the indirect spillover effects of technological innovation total about 0.33 (0.21+0.12), accounting for over 50% of the total effect (0.33/0.61 ≈ 54.1%). This indicates that relying solely on direct technological input to increase agricultural output is not the only path to ensuring food security. Technological innovation can empower the entire grain industry chain, covering various nodes such as seed research and development, planting management, harvest and storage, processing and transportation, and market circulation. The synergistic improvement of efficiency in each link jointly builds a solid guarantee for food security.

Reverse feedback effect (FS → TI): Food security has a significant positive driving effect on technological innovation, with a path coefficient of 0.22 and passing a statistical significance test at the 5% level. In the macro environment of sufficient food supply and stable market operation, the government and agricultural operators have stronger investment willingness and financial strength to carry out agricultural research and development activities, thereby further consolidating and strengthening the existing effectiveness of food security guarantee. The two exhibit a bidirectional virtuous cycle relationship: the higher the level of food security, the more conducive it is to the iterative progress of agricultural technology; And the advancement of agricultural technology will in turn continue to strengthen the ability to ensure food security.

Indirect Effect III (TI → (RC × SCM) → FS): Technological innovation can strengthen the synergistic linkage effect between supply chain management (SCM) and risk control (RC), and indirectly promote food security (FS) through this synergistic mechanism. The impact of technological innovation on the RC × SCM synergy factor can be understood as the synchronous promotion of agricultural management entities in optimizing supply chain management and enhancing risk prevention and control capabilities through technological innovation, thereby building a mutually reinforcing and synergistic development environment. The collaborative mechanism is specifically reflected in the significant positive impact of technological innovation on supply chain management (SCM) and risk control (RC), and the optimization and improvement of each of them are transformed into a greater contribution to food security (FS) through interactive linkage effects. The empirical results show that the indirect effect of technological innovation on food security through the RC × SCM collaborative path is significantly positive, and this transmission path accounts for a considerable proportion of the total effect of technological innovation on food security, highlighting the dual value of "technological empowerment+collaborative management".

The empirical results of structural equation modeling (SEM) verify that technological innovation has significant indirect spillover effects on food security (FS) through the dual mediating path of supply chain management (SCM) and risk control (RC), and the scale of such indirect spillover effects is comparable to that of direct effects. At the same time, the synergistic enhancement effect of supply chain management and risk control can significantly amplify the positive driving effect of technological innovation on food security, confirming the synergistic effect of "technological innovation+collaborative management". In addition, the improvement of food security level will further promote agricultural technological progress in reverse. The achievement of food security goals can enhance the innovation confidence of the government and agricultural operators, increase their willingness to invest in innovation, and ultimately form a two-way promotion and virtuous cycle interaction between agricultural technological innovation and food security. Therefore, in promoting food security, equal attention should be paid to the coordinated development of technological innovation and management innovation. On the one hand, technological innovation can directly enhance agricultural production capacity, and on the other hand, through optimizing supply chain management efficiency and reducing agricultural production risks, indirect paths can be taken to further increase food production and stabilize food supply, ultimately achieving sustainable improvement in food security levels.

5.3 Robustness Test

5.3.1 Instrumental Variable (IV) Regression Results

This article selects the intensity of agricultural science and technology policies, the level of agricultural subsidies, and the density of regional scientific researchers as instrumental variables, and constructs a two-stage least squares (2SLS) model to re-examine the impact of technological innovation (TI), supply chain management (SCM), and risk control (RC) on food security (FS). The intensity of agricultural technology policies can meet the requirements of instrumental variable correlation: government policy support in areas such as agricultural technology research and development, supply chain infrastructure construction, and agricultural insurance system improvement will directly drive regions and agricultural operators to continuously increase investment in technological innovation, promote supply chain modernization transformation, implement risk control measures such as agricultural insurance, and significantly affect the levels of TI, SCM, and RC. In terms of exogeneity, although ensuring food security is a national macro policy goal, policy variables such as agricultural technology special support and fiscal subsidy scale are mainly driven by external factors such as fiscal budget constraints, long-term industrial planning, and policy cycles. There is no direct causal relationship with the short-term provincial food production situation. The impact of agricultural science and technology policies on food security is indirectly transmitted through intermediary channels such as technological innovation, supply chain optimization, and risk control improvement, rather than forming direct exogenous shocks or decisive interventions on food production.

Agricultural subsidies and their allocation can influence companies or farmers' investments in technology research and development, modernization of supply chains, and insurance coverage. However, the basis for subsidy distribution is more often the fiscal planning or policy guidance of various levels of government; regional food security is not the sole or rapidly adjustable factor[24]. For a period, agricultural subsidies and FS are unlikely to form a tight, immediate "unidirectional causal" relationship; instead, they indirectly affect FS by promoting TI, SCM, and RC.

The concentration of researchers enhances the atmosphere and resource supply for agricultural technological innovation, shortens the cycle for enterprises to acquire and convert new technologies, and also promotes the adoption of modern supply chain management methods. It provides intellectual support for agricultural risk assessment and insurance product design. The distribution of researchers or research institutions does not immediately shift or increase or decrease [25] due to changes in grain production (FS) in a specific year or region. During the study period, these factors remain relatively stable, thus having no direct causal impact on FS, which meets the requirement of exogeneity for the explained variable in instrumental variables.

The IV regression results show that the impact coefficients of TI, SCM, and RC on food security are all positive and statistically significant, supporting the core conclusion. The interaction term between SCM and RC is also positive and significant in both models, which supports the hypothesis that "SCM × RC synergy" can amplify the positive effects of TI on food security. Table 5 compares the coefficients estimated by the IV approach with those from the benchmark fixed effects model (FE).

Table 5: Instrumental variable method (IV) regression results

variable	FE estimate	IV estimate
variable (TI)	0.052***	0.078***
supply chain management (SCM)	0.034**	0.030**
Risk control (RC)	0.028**	0.026**
RC×SCM (Interaction term)	0.010**	0.012**

Note: *, **, *** indicate significance at the 10%,5%, and 1% levels, respectively.

After using the instrumental variable, the positive effect of the core independent variable on food security is still significant, and the coefficient is roughly consistent with the results of the FE model. After controlling for endogeneity, the conclusion is still robust. Technological innovation, supply chain management, risk control and the interaction between supply chain management and risk control all significantly improve the level of food security.

5.3.2 Analysis results of propensity score matching (PSM)

Further, the PSM method was employed to divide samples into high TI and low TI groups based on the level of technological innovation input, and matched according to per capita GDP, population, and arable land area to evaluate the average treatment effect (ATT) of technological innovation on food security. After matching, there were no significant differences between the high TI and low TI groups in covariates, satisfying the balance assumption. The food security level of the high technological innovation group was significantly higher than that of the low technological innovation group. Specific ATT estimates are shown in Table 6.

Table 6: ATT estimation results

Average treatment effect (ATT)	Standard error
0.08**	0.03

The positive ATT and significant at the 5% level indicate that, under similar conditions, the food security index of regions (or enterprises) with high investment in technological innovation is on average about 0.08 higher than that of the low investment group, supporting the conclusion that technological innovation contributes to improving food security.

5.3.3 Regression results of alternative variables

Three different food security alternative indicators were used for regression analysis: (1) total grain production (reflecting the capacity to supply food), (2) self-sufficiency rate (grain production/consumption ratio), and (3) per capita grain availability. The regression results show that, regardless of which food security measure is used, the coefficients for technological innovation (TI), supply chain management (SCM), and risk control (RC) are all positive and mostly significant at the 5% or higher significance level.

In the regression of three alternative dependent variables—total grain production, self-sufficiency rate, and per capita grain possession—the coefficients of TI, SCM, RC, and RC×SCM are all positive, with most being significant at the 1% or 5% level. This indicates that whether grain security is measured by production, self-sufficiency, or per capita possession, the positive impact of technological innovation, supply chain management, risk control, and their interactive relationship on grain security remains unchanged.

6 Research conclusions and policy recommendations

6.1 Research conclusions

Research hypothesis verification. As shown in Table 7.

1. Assumption 1A (Technological innovation to food security)

The research findings indicate that technological innovation has a significant positive impact on food security. In the panel regression analysis, the regression coefficient of technological innovation is significant at the 1% level ($\beta=0.152$, $p<0.01$), and in the SEM model, the direct effect path coefficient is 0.28 ($p<0.01$). This result suggests that technological innovation (including agricultural R&D investment and patent numbers) can directly enhance grain production and supply stability, thus supporting Hypothesis 1A.

2. Assumption 1B (food security to technological innovation)

The results of the reverse regression model show that food security significantly promotes technological innovation, with a regression coefficient of 0.130 ($p<0.01$). In the SEM model, the reverse path coefficient is 0.22 ($p<0.05$). This indicates that improving food security will increase the willingness of enterprises and governments to invest in agricultural research and development, forming a virtuous cycle of technological innovation, thus supporting Hypothesis 1B.

3. Hypothesis 2 (the mediating role of supply chain management)

Supply Chain Management (SCM) plays a partial mediating role between technological innovation and food security. In the SEM analysis, the path coefficient of technological innovation on SCM is 0.55 ($p<0.01$), and the path coefficient of SCM on food security is 0.38 ($p<0.05$). The indirect effect reaches 0.21, accounting for 43% of the total effect, thus Hypothesis 2 holds.

4. Hypothesis 3 (The mediating role of risk control)

Risk control (RC) also plays an intermediary role between technological innovation and food security. The path coefficient of technological innovation on risk control is 0.47 ($p<0.01$), and the path coefficient of risk control on food security is 0.26 ($p<0.05$). The indirect effect is approximately 0.12, accounting for 18% of the total effect. Hypothesis 3 holds

Table 7: Regression coefficients of three core variables under different dependent variables

variable	Total grain output	Grain self-sufficiency rate	Per capita grain possession
Technological innovation (TI)	0.22***	0.04**	0.15***
Supply Chain Management (SCM)	0.15**	0.03*	0.10**
Risk control (RC)	0.18**	0.05**	0.12***
RC×SCM (Interaction term)	0.11*	0.04**	0.07*

5. Hypothesis 4 (The interaction between supply chain management and risk control)

The interaction term between supply chain management and risk control (RC×SCM) has a significant impact on food security in both the panel regression model ($B=0.022$, $p<0.01$) and the SEM analysis (path coefficient 0.30, $p<0.01$). Effective supply chain management and risk control can synergistically enhance the promoting effect of technological innovation on food security, thus hypothesis 4 holds.

All research hypotheses were supported, indicating that technological innovation, supply chain management, and risk control form important mechanisms for enhancing food security and create a positive interactive relationship. Multiple robustness tests confirmed the reliability of these conclusions. By changing the food security measure (from per capita grain availability to self-sufficiency rate) and controlling for regional fixed effects, the direction and significance of the core independent variable remained largely unchanged, with coefficient changes within reasonable ranges. This suggests that the model conclusions are not specific to particular model settings or indicator choices but have general applicability and robustness.

6.2 Policy Recommendations

The government should organically integrate technological innovation, supply chain management, and risk control into the design and implementation of the food security policy system: (1) It is necessary to increase investment in agricultural technology innovation, focus on strengthening policy and financial support for cutting-edge fields such as high-yield and stress resistant crop variety cultivation, intelligent agricultural equipment research and development, and digital agricultural technology application, and promote the transformation of agricultural technology towards precision, intelligence, and efficiency. (2) The government should establish a long-term stable investment mechanism, continuously increase the scale of agricultural research funding allocation, build an efficient bridge between scientific research achievements and agricultural production, and promote the rapid transformation of cutting-edge science and technology into actual agricultural productivity. (3) We should actively guide agricultural enterprises and research institutions to carry out in-depth industry university research cooperation, focus on key technological bottlenecks in agricultural production and food security, and jointly tackle and innovate. (4) Continuous and stable technological investment and a comprehensive technology promotion system will become the fundamental support for ensuring food security.

In promoting the modernization of the grain supply chain, (1) we will further increase the construction and upgrading of infrastructure such as grain storage facilities, cold chain logistics systems, and production site transportation equipment. By improving the layout of infrastructure, we will effectively reduce the loss rate of grain throughout the entire chain from post harvest, warehousing and storage, transportation and circulation to terminal distribution. (2) The government can encourage agricultural leading enterprises, farmer professional cooperatives, and e-commerce platforms to deepen cooperation and build an integrated grain supply chain system of "production storage circulation sales" through policy guidance, financial support, and other means. (3) By optimizing the operation process of the supply chain, improving the industry standard system, and strengthening full process supervision, we aim to stabilize the supply of grain in the market, ensure effective supply of grain, and broaden channels for increasing farmers' income.

Improve the agricultural risk prevention and control system, establish a sound risk management mechanism: (1) Further expand the coverage of agricultural insurance, steadily promote the implementation of insurance policies for major grain varieties, optimize the agricultural insurance subsidy mechanism, continuously improve farmers' participation in insurance and insurance compensation standards, and strengthen the protection of agricultural production risks. (2) It is necessary to strengthen the construction of agricultural disaster warning and emergency response system, establish early monitoring, accurate warning and pre prevention and control mechanisms for weather conditions, crop pests and diseases, and achieve "early detection, early warning, and early disposal" of agricultural disasters, and minimize the impact of disasters on food production. (3) We should actively guide agricultural operators to develop moderate scale operations, optimize the diversity of planting structures, enhance risk resistance through large-scale layout, diversify individual business risks through diversified planting, reduce the adverse effects of fluctuations in grain production, and stabilize grain production expectations.

At the overall strategic level, (1) technological innovation, supply chain optimization, and risk prevention should be regarded as the "three pillars" and systematically incorporated into the national food security action plan for coordinated promotion. (2) Relevant departments such as agriculture and rural areas, science and technology, transportation, emergency management, etc. need to break down departmental barriers, strengthen collaborative linkage, jointly formulate targeted policy tools, and form a working force in key areas such as grain storage, logistics circulation, technology research and development, and agricultural insurance to promote the coordinated efforts and effective implementation of various policies. (3) A scientific and comprehensive policy implementation monitoring and evaluation mechanism should be established to regularly quantify the actual impact of policy implementation on grain production, supply chain circulation efficiency, and agricultural risk resistance. Based on the evaluation results, policy content and implementation paths should be dynamically adjusted and optimized to ensure rational and efficient resource allocation, fully leverage policy synergies, and enhance the systematicity and sustainability of food security.

Building a long-term mechanism to promote a virtuous cycle between food security and technological innovation: (1) The government should establish stable funding channels and increase sustained financial support for agricultural scientific and technological innovation and food security; (2) Improve policies for cultivating, introducing, and incentivizing agricultural science and technology talents, and consolidate the foundation of agricultural science and technology innovation talents; (3) Actively guide agricultural enterprises, universities, and research institutions to collaborate deeply, focus on major technological challenges in the agricultural field, and carry out joint research and development to enhance the overall efficiency of agricultural technology innovation. (4) Provide rewards and policy support to farmers and agricultural operators who successfully apply new agricultural technologies and models, cultivate a healthy agricultural science and technology innovation ecosystem, and promote the rapid transformation and application of agricultural science and technology innovation achievements.

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