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Digital Technology Empowerment for Enhancing Food Security Resilience: Theoretical Logic, Realistic Challenges, and Breakthrough Pathways

Linwei Wang

Chongqing Academy of Social Sciences, Chongqing, China
wlwnancykk@163.com

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Abstract: Food security constitutes a cornerstone of national security, and enhancing food security resilience is an imperative strategy for addressing complex and uncertain challenges. Digital technologies, with their distinct advantages in perception, connectivity, computation, and intelligent decision-making, offer novel technological pathways and institutional space for bolstering food security resilience. Grounded in a clear delineation of the conceptual connotation of food security resilience, this paper constructs a three-dimensional analytical framework comprising technology, organization, and institutions to systematically elucidate the intrinsic mechanisms through which digital technologies empower the enhancement of food security resilience. The findings reveal that digital technologies enhance resilience through multiple pathways. Precise perception strengthens risk early warning capacities. Intelligent decision-making optimizes emergency response mechanisms. Collaborative platforms restructure industrial chain organizational models. Data governance improves the agility of institutional responses. However, practical implementation faces several dilemmas, including bottlenecks in the last mile of digital infrastructure, siloed agricultural data and collaborative barriers, structural mismatches between institutional supply and technological iteration, and insufficient accumulation of digital human capital. To address these issues, coordinated efforts are required to solidify the digital foundation, foster a data-sharing ecosystem, refine institutional adaptability systems, and cultivate interdisciplinary talent pools. These measures will establish a long-term mechanism for leveraging digital technologies to enhance food security resilience.

1. Introduction

Food security is a paramount national priority and a fundamental pillar of national security. Against a backdrop characterized by intensifying global climate change, frequent geopolitical conflicts, sharp fluctuations in international agricultural markets, and major public health emergencies, traditional food security systems face unprecedented shocks and challenges[1]. Food security resilience refers to the comprehensive capacity of the food system across production, distribution, reserves, and consumption to withstand shocks, adapt rapidly to changing conditions, and recover promptly while optimizing operational performance when confronted with uncertainties such as natural disasters, drastic market fluctuations, trade disruptions, and public health emergencies. It serves as a critical benchmark for evaluating the maturity of a nation's food security system[2]. In recent years, the relevant authorities have successively issued a series of policy documents, explicitly requiring the use of digital technologies to empower the transformation and upgrading of the grain industry, thereby strengthening the resilience and flexibility of the food system in responding to risks and challenges. Nevertheless, China's food security system still confronts deep-seated problems such as bottlenecks in seed industry development, the continuous degradation of cultivated land quality, prominent structural imbalances between production and demand, and the increasing vulnerability of grain supply chains, making it imperative to enhance food security resilience.

The rapid advancement and widespread penetration of digital technologies in agriculture have created unprecedented technical conditions and institutional space for enhancing food security resilience. Next-generation digital technologies, including the Internet of Things, big data, artificial intelligence, blockchain, satellite remote sensing, and 5G, are profoundly reshaping the underlying operational logic across all stages of grain production, distribution, storage, and consumption. From precision agriculture and intelligent warehousing and logistics to blockchain-based traceability, digital technologies are comprehensively enhancing the capacity of the food system to cope with uncertain shocks across four dimensions, namely perception, decision-making, execution, and feedback[3]. Academic research on food security concentrates on three domains: First, studies on the evolution of food security connotations and evaluation index systems, focusing on the expansion from quantitative security toward quality security and nutritional security[4]. Second, research on institutional and mechanism reforms, exploring the logic of institutional guarantees from dimensions such as land systems, price support, reserve regulation, and trade policies[5]. Third, studies on the relationship between agricultural technological innovation and food production increase and quality improvement, focusing on the roles of seed industry innovation, cultivated land protection, and green production technologies[6]. Some scholars have also begun to examine topics such as agricultural resilience measurement, food supply chain resilience, and farmers' risk resistance capacity[7-9]. However, research directly focusing on how digital technologies systematically empower the enhancement of food security resilience remains insufficient, lacking a systematic analytical framework that integrates the technological, organizational, and institutional dimensions. Against this backdrop, this paper constructs a three-dimensional Technology-Organization-Institution analytical framework to systematically elucidate the intrinsic mechanisms, practical dilemmas, and breakthrough pathways through which digital technologies empower food security resilience.

2. Theoretical Logic of Digital Technology Empowerment for Enhancing Food Security Resilience

2.1. Conceptual Connotation and Core Elements of Food Security Resilience

The concept of resilience originated in ecology and engineering before being introduced to social sciences, where it became a crucial analytical tool for risk governance and sustainable development research[10]. In economic resilience studies, resilience is generally defined as the capacity of a system to absorb disturbances amid external shocks, maintain core functions through adaptive adjustments, and achieve self-recovery and upgrading. Introducing the resilience concept into the field of food security, food security resilience denotes the integrated capacity of the food system spanning production, distribution, reserves, and consumption to resist disturbances, adapt expeditiously to evolving circumstances, and restore and optimize operations in response to uncertainties including natural calamities, severe market turbulence, trade interruptions, and public health emergencies[11].

The core elements of food security resilience can be summarized at three levels. First, resistance, which is the ability of the food system to maintain basic output and supply levels when faced with shocks; this depends on the fundamental conditions of food production, the scale of reserves and the redundancy of the supply chain, amongst other factors[12]. Second, adaptability, which is the ability of the food system to respond to external disturbances by adjusting production structures, optimizing distribution channels and altering consumption behavior; this depends on the system’s capacity to access information, the flexibility of decision-making and the efficiency of resource reallocation[13]. Third, recovery and transformation capacity, which refers to the food system’s ability to return to its original functional state after a shock, or even to achieve structural optimization and a leap in performance levels; this depends on the level of technological innovation, institutional flexibility and organizational learning capacity[14].

2.2. Intrinsic Mechanisms of Digital Technology Empowerment for Food Security Resilience

The empowering effect of digital technologies on food security resilience does not stem from the simple superposition of individual technological elements. Rather, it arises from a systematic process involving technological embedding, organizational restructuring, and institutional optimization.

First, the mechanism at the technological dimension involves precise perception and intelligent decision-making reshaping risk response logic. On the production side, an integrated space-air-ground monitoring network composed of satellite remote sensing, drone patrols, and ground sensors captures real-time critical information such as crop growth, soil moisture, and pest occurrence. This transforms production management from experience-based judgment to data-driven precision decision-making, significantly enhancing the capacity of the grain production system to withstand natural disaster risks. On the distribution side, the integration of IoT devices and big data enables real-time dynamic monitoring of grain transportation vehicles, storage environments, and market prices. By capturing early signals of abnormal fluctuations, the system can automatically trigger warnings and provide tiered response recommendations, shortening the time window from risk identification to response decision-making. On the reserve side, AI-based supply and demand forecasting models dynamically optimize decisions regarding reserve scales and release timing based on coupled analysis of historical data and real-time variables, thereby improving the precision and efficiency of reserve resources in responding to sudden shocks.

Second, the mechanism at the organizational dimension involves platform-based collaboration and decentralized restructuring enhancing industrial chain resilience. Digital technologies not only alter information flow patterns but also reshape the organizational forms and collaboration logic of the grain industrial chain. For instance, digital platforms integrate entities across the entire chain, including production, processing, logistics, and sales, forming virtual industrial alliances. This reduces transaction costs and information friction between links, bolstering the overall coordination capacity of the industrial chain when facing localized shocks. Furthermore, the decentralized and tamper-proof nature of blockchain technology establishes a transparent and traceable trust mechanism for the grain supply chain. Full-process information recording from production sources to consumption terminals enables precise localization and rapid isolation of quality, safety, and compliance risks, effectively curbing the amplification effect of risk propagation along the industrial chain. Additionally, e-commerce platforms and digital payment systems shorten the connection distance between production and consumption ends, mitigating the impact of local market imbalances on overall food security.

Third, the mechanism at the institutional dimension involves enhanced agility in data governance and policy responses. The establishment of agricultural big data platforms shifts food security decision-making from sampling estimation to full-population computation. Policymakers can leverage multi-source, high-frequency, high-precision data to timely grasp grain production situations, market dynamics, and risk evolution trends, providing data support for the timely adjustment and targeted deployment of policy instruments. Concurrently, digital supervision technologies, such as satellite remote sensing verification and intelligent monitoring systems, substantially reduce policy implementation supervision costs while greatly enhancing verification accuracy, thereby mitigating information distortion and moral hazards during policy execution. Moreover, digital technologies perform a learning and evolution function at the institutional level. Real-time assessment and feedback mechanisms regarding policy effectiveness endow institutional supply with dynamic adjustment capabilities, enabling rapid iterative optimization in response to environmental changes and strengthening the resilience of the institutions themselves.

2.3. Logical Interconnections within the Three-Dimensional Technology, Organization and Institution Analytical Framework

Within the process of digital technology empowerment for food security resilience, the technological, organizational, and institutional dimensions do not operate in isolation. Instead, they exhibit deeply inter-embedded and co-evolving logical connections. The technological dimension constitutes the foundational layer, providing core capacities in perception, connectivity, computation, and intelligent analysis. The organizational dimension serves as the connective layer, translating technological capacities into substantive enhancements in industrial chain resilience through platform-based transformation and collaborative mechanism innovation. The institutional dimension acts as the safeguarding layer, furnishing the legitimacy basis and operational boundaries for technological empowerment and organizational reform through data governance, policy innovation, and regulatory adaptation. These three dimensions form a recursive cycle characterized by technology driving organizational responses and organizations necessitating institutional innovation, while institutional progress creates a more conducive environment for deeper technological application. This generates a spiral trajectory of empowerment evolution.

3. Practical Dilemmas in Digital Technology Empowerment for Enhancing Food Security Resilience

3.1. Bottlenecks in the Last Mile of Digital Infrastructure and the Production-Side Divide

Digital infrastructure serves as the material prerequisite for digital technology empowerment. However, significant regional disparities and structural shortcomings persist in the construction of digital infrastructure for agriculture in China. On one hand, although the coverage of rural broadband networks, 5G base stations, and IoT sensor nodes continues to improve, a marked gap remains between major grain-producing regions in central and western China and developed eastern regions. On the other hand, existing agricultural digital infrastructure predominantly focuses on the initial digitization of production processes. Coverage depth and system integration remain inadequate in areas critically linked to food security resilience, such as intelligent warehousing and logistics, digital traceability of agricultural products, and informatization of emergency reserves. The rural digital divide manifests not only as disparities in hardware facilities but also as constraints related to low digital literacy among farmers and high costs for smallholders to access digital systems. These factors impede the scaled adoption and deep application of digital technologies at the grain production end.

3.2. Siloed Agricultural Data and Barriers to Industrial Chain Collaboration

Data constitutes the core factor of production in the digital era, and its fluid sharing is a prerequisite for digital technologies to empower food security resilience. However, the current data governance system in the agricultural sector remains underdeveloped, with prominent issues of data silos and departmental barriers. First, various departments, including agriculture, food security, meteorology, market regulation, and transportation, possess data resources pertinent to food security. Yet, inconsistent data standards, incompatible interfaces, and absent sharing mechanisms among these departments prevent the cross-departmental flow and integrated utilization of data. Second, enterprises across the grain industrial chain, spanning seeds, agricultural inputs, production, processing, storage, logistics, and sales, hold proprietary commercial data. Due to concerns over profit protection, business confidentiality, and competitive advantage, there is a lack of both intrinsic motivation and external binding mechanisms for sharing this data, resulting in fragmented data flows across the chain. Third, rules regarding data ownership, pricing, and transactions are still exploratory. Ambiguous property rights over data assets and an imperfect legal framework for data security and privacy protection further constrain the circulation efficiency of data factors.

3.3. Structural Mismatch Between Institutional Supply and Technological Iteration

Institutional systems governing food security have evolved gradually over long periods of practice, exhibiting characteristics of relative stability and path dependency. However, the iteration speed of digital technologies far outpaces the update rhythm of traditional institutional systems. This speed differential creates a structural mismatch between institutional supply and technological demand, posing a deep-seated obstacle to digital empowerment. Specific manifestations include the following. Existing food security regulatory institutions are largely designed around traditional information collection and reporting workflows, making them ill-suited to accommodate the operational demands of real-time monitoring, high-frequency interaction, and intelligent decision-making under digitalized conditions. Furthermore, underdeveloped rules governing cross-border data flows constrain the application of digital technologies in international grain trade and global supply chain management. Amid escalating international market volatility, cross-border data flows involved in grain import and export face institutional constraints related to data sovereignty and security, lacking mature institutional arrangements for balanced regulation. Additionally, the application of digital technologies in the grain sector raises novel governance issues concerning data collection boundaries, algorithmic decision-making accountability, and privacy protection.

3.4. Shortcomings in Talent for Digital Governance of Food Security

Human capital represents the most dynamic and decisive factor in productivity. Ultimately, realizing the potential of digital technologies to enhance food security resilience depends on interdisciplinary talents possessing both digital literacy and expertise in food security. However, the current landscape reveals a severe structural shortage of such talent. On one hand, the supply of digital professionals in agriculture is grossly inadequate. Major grain-producing regions face enormous gaps in information technology personnel, directly constraining the on-the-ground implementation of digital technologies in production, distribution, and reserve management. On the other hand, grassroots agricultural administrators generally exhibit low digital literacy. Cognitive deficiencies and operational barriers regarding emerging technologies, such as big data analytics, AI-driven decision-making, and blockchain traceability, lead to prevalent phenomena where advanced digital systems, once introduced, suffer from non-use or suboptimal use.

4. Breakthrough Pathways for Digital Technology Empowerment in Enhancing Food Security Resilience

4.1. Solidifying the Digital Foundation and Bridging the Agricultural Digital Divide

Digital infrastructure serves as the material cornerstone for digital technology to empower food security resilience. The government should coordinate the advancement of digital infrastructure in major grain-producing regions, focusing on remedying the informatization shortcomings in central and western regions. Agricultural and rural authorities should accelerate the extension of rural broadband and 5G coverage, promote the scaled deployment of IoT sensing devices in core grain production zones, large-scale storage bases, and logistics nodes, and build an integrated space-air-ground situational awareness network. Grain and reserve authorities should advance the intelligent retrofit of storage facilities, establish a nationally unified digital management platform for grain reserves, and implement real-time dynamic supervision over the quantity, quality, and environment of stored grain. Fiscal authorities should strengthen digital assistance for smallholder farmers, reducing their cost of accessing digital systems through subsidies and service outsourcing, so as to ensure that the benefits of empowerment reach all agricultural operators.

4.2. Constructing a Shared Food-Related Data Ecosystem and Eliminating Industrial Chain Collaboration Blockages

Breaking down data silos and promoting the efficient circulation of food-related data is the key to unlocking the empowerment potential of digital technology. National data governance authorities should take the lead in establishing a data standard system for food-related sectors, unifying data formats, interfaces, and metadata standards to lay the foundation for cross-departmental and cross-level data sharing. Agricultural and rural authorities, together with grain, meteorological, market regulation, and transportation authorities, should build a national-level food-related data sharing and exchange platform to promote the orderly sharing and aggregation of core data. Market regulation authorities should explore data rights confirmation and trading mechanisms, clarify the boundaries of data ownership, usage rights, and revenue rights, and guide enterprises to open up industrial chain data on the premise of protecting trade secrets.

4.3. Refining the Institutional Adaptability System to Enhance Governance Agility

Institutional agility is a key requirement for matching the rapid iteration of digital technology. Legislative authorities should accelerate the digital transformation of laws and regulations governing food security, revise and improve the supporting regulations of the Food Security Law, and bring digital monitoring and intelligent decision-making into the legal framework. Agricultural and rural authorities should build a grain market monitoring and early warning platform based on big data and artificial intelligence, achieving a paradigm shift from static sampling reporting to dynamic full-scale analysis. Development and reform authorities should establish a dynamic adjustment mechanism between digital technology and institutions, set up regulatory sandbox pilot zones for digital governance in agriculture, and allow emerging technologies to be piloted and institutions adjusted in a timely manner. Commerce authorities should actively participate in the formulation of rules for cross-border data flows and digital trade related to food, aligning with high-standard international rules.

4.4. Cultivating an Interdisciplinary Talent Pool to Strengthen the Human Capital Foundation

Talent is the fundamental guarantee for digital technology to empower food security resilience. Education authorities, together with agricultural and rural authorities, should advance the construction of interdisciplinary programs integrating digital technology with agriculture, establishing directions such as smart agriculture and digital food security management that cover core courses including big data, artificial intelligence, IoT, and blockchain. Agricultural and rural authorities should rely on the high-quality farmer cultivation program to provide digital literacy training for large-scale grain growers, cooperative leaders, and grassroots granary managers, bridging the final gap in technology implementation at the grassroots level. Organization and human resources authorities should improve mechanisms for recruiting and incentivizing digital talent, offering policy preferences in housing and professional title evaluation in major grain-producing regions. Leading agricultural enterprises and digital technology companies should jointly build industry-education-research integration bases with universities and research institutes, forming a virtuous cycle of co-cultivating talent and sharing achievements.

5. Conclusion

Food security resilience represents a crucial dimension of the food security strategy in the new era. Digital technologies provide unprecedented technical conditions and institutional space for enhancing this resilience. This paper delineates the conceptual connotation of food security resilience from a theoretical standpoint and constructs a three-dimensional Technology-Organization-Institution analytical framework. It systematically elucidates the intrinsic mechanisms through which digital technologies empower food security resilience. The research finds that digital technologies enhance the resistance, adaptation, and recovery capacities of the food system through triple pathways involving technological embedding, organizational restructuring, and institutional optimization. However, practical implementation encounters multiple dilemmas. These include bottlenecks in the last mile of digital infrastructure, siloed agricultural data and barriers to industrial chain collaboration, structural mismatches between institutional supply and technological iteration, and structural shortages of interdisciplinary talent. Effectively resolving these dilemmas necessitates coordinated actions across four fronts. Solidifying the digital foundation bridges the digital divide. Constructing a data-sharing ecosystem eliminates collaboration blockages. Refining institutional adaptability enhances governance agility. Cultivating talent pools strengthens the human capital base. Together, these efforts will accelerate the formation of a long-term mechanism for digital technology empowerment in enhancing food security resilience.

It must be noted that empowering food security resilience through digital technologies is not merely a technical project achievable overnight. Rather, it constitutes a systemic evolution involving technological application, organizational transformation, and institutional innovation. With the rapid advancement of frontier technologies such as artificial intelligence, quantum computing, and edge computing, the modalities and boundaries of digital technology empowerment will continue to expand. Concurrently, evolving external uncertainties, including global climate change, geopolitical maneuvering, and trade frictions, pose fresh challenges to food security resilience governance. Consequently, the topic of digital technology empowerment exhibits distinctly dynamic evolutionary characteristics, demanding sustained scholarly and policy attention. Future research could focus on several avenues. First, conduct empirical econometric analyses on the empowerment effects of digital technologies, utilizing micro-survey data and macro-panel data to test the efficacy of different technological pathways and their heterogeneity. Second, delve deeper into the differentiated mechanisms of digital technologies across various resilience dimensions, specifically pre-crisis risk warning, in-crisis emergency response, and post-crisis recovery and transformation. Third, incorporate novel institutional factors, such as digital economy rules, data sovereignty, and international digital trade, into the analytical framework to broaden the international perspective and institutional depth of the research.

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