Research on the Application and Diffusion Mechanism of Digital Technology in the Agricultural Value Chain Empowered by New Quality Productivity

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Abstract: Digital technology is gradually becoming the core engine driving the modernization of agriculture. The digital transformation in the agricultural sector has a profound impact on the organizational model and operation mechanism of the agricultural value chain. At the same time, new quality productive forces, with their unique technical penetration, network collaboration, and data-driven capabilities, play an important role in the agricultural field. However, the actual diffusion effect of new quality productive forces in the agricultural value chain still shows significant differences, especially in terms of the degree of technology adoption among different entities, the depth of collaboration, and the efficiency of resource integration. These differences restrict the overall promotion and efficiency improvement of agricultural digitalization. This paper focuses on the diffusion mechanism of digital technology in the agricultural value chain and conducts research by constructing a dynamic mathematical model to analyze the core driving factors affecting the diffusion of technology and the actual effects of policy intervention. It is found that new quality productive forces can effectively enhance the overall technical application level of the agricultural value chain through two paths: vertical diffusion and horizontal diffusion. On this basis, to better promote the efficient dissemination and deep application of agricultural digital technology, further policy recommendations are proposed.

***Keywords*:** new quality productive forces; agricultural value Chain; digital technology; diffusion mechanism

1. Introduction

With the continuous breakthroughs of emerging technologies such as big data, artificial intelligence, blockchain and the Internet of Things, the new quality productive forces centered on digital technology have become increasingly mature. This has driven the digital development of the agricultural value chain to gradually shift from local technical exploration to a systematic and large-scale transformation stage. It not only changes the organizational mode and operation methods of traditional agricultural production, but also further reshapes the collaboration relationships, resource integration mechanisms and overall competitive landscape among all entities in the agricultural value chain, promoting the agricultural economy to develop in a more efficient and collaborative direction.

2. Problem Statement

The agricultural value chain serves as a crucial link that integrates the production, processing, distribution, and consumption stages of agriculture. The degree of its digital transformation directly affects the efficiency of agricultural economic operation and the level of sustainable development. However, the current digital development of the agricultural value chain still faces numerous structural obstacles, and the uneven characteristics during the process of technology diffusion are more pronounced, making it difficult to further promote the digital transformation of agriculture and ultimately affecting the overall effectiveness of agricultural modernization. On one hand, it is manifested as leading entities in the value chain, such as Leading enterprises or digital platforms, who often rapidly implement digital technology applications and upgrades by leveraging their financial advantages and technical resources. Meanwhile, small and medium-sized farmers or cooperatives in disadvantaged positions, due to insufficient funds, weak technical acceptance capabilities, and relatively backward infrastructure, are unable to fully integrate into the digital transformation process, resulting in a significant technological gap between the entities. On the other hand, the technical collaboration mechanism among different links within the value chain is not yet complete, information silos are widespread, and the efficiency of data flow and resource integration among links is insufficient, restricting the in-depth penetration and systematic application of digital technology throughout the agricultural value chain[1].

This paper takes the diffusion mechanism of digital technology as the entry point to study the theoretical logic and implementation path of new quality productive forces empowering the development of the agricultural value chain. It conducts analysis around two core issues: First, how can new quality productive forces promote the overall upgrading of the chain through the vertical and horizontal dissemination of digital technology? Second, in the context of multi-party interaction, how do policies affect the efficiency of technology diffusion and the formation and strengthening of collaboration networks? In terms of theoretical methods, this paper constructs a dynamic mathematical model to conduct quantitative analysis of the key driving factors in the digital technology diffusion process, revealing the linkage mechanism of technological level differences, connection strength, and policy variables in the diffusion dynamics, and further clarifying the mechanism of policy in optimizing the diffusion path, enhancing technical absorption capacity, and promoting the collaborative upgrading of the value chain. The aim is to provide theoretical support and policy recommendations for the digital transformation of the agricultural value chain.

3. Empowering Agricultural Digital Technology Diffusion Mechanism and Model Construction with New Quality Production Forces

3.1 New Quality Production Forces and Digitalization of Agricultural Value Chain

New quality production forces, as a new form of productive forces in the era of digital economy, differ from the traditional productive force system based on material factors and resource endowments. Through the deep integration and systematic embedding of digital technologies, they break the constraints of resource endowments and physical space on the production process, achieving a leap in production efficiency and efficient and refined resource allocation. New quality production forces are driven by data, algorithms, and intelligent systems, reconfiguring the interlocking logic and operation mechanism among production, circulation, and consumption, forming a new economic organizational form characterized by networking, intelligence, and platformization, and driving the systematic transformation and continuous optimization of production methods and consumption structures.

Digitalization of agricultural value chain is the specific application of the concept of new quality production forces in the agricultural field. Centered on data, through the embedding, penetration, and empowerment of digital technologies, the traditional agricultural value chain gradually evolves into a complex system that is intelligent, collaborative, and ecological. It is manifested as a comprehensive digital transformation of the entire value chain from the production source to the consumption terminal. Its fundamental goal is to significantly improve the operational efficiency of the agricultural value chain, enhance the ability to create value, and promote the sustainable development of the agricultural economy.

3.2 Digital Technology Diffusion Mechanism: Vertical Diffusion and Horizontal Diffusion

In the process of digitalization of agricultural value chain, the effectiveness of new quality production forces depends on the degree of diffusion and application of digital technologies. This diffusion process has two different paths: vertical diffusion is the flow and dissemination of technology along different links of the agricultural value chain, which can extend from the production end to the consumption end step by step, or can be driven by market demands at the terminal end to promote technological upgrading at the production end. For example, in precision agriculture, planting technologies spread from the production link to the processing link, guiding the application of intelligent equipment, thereby improving the efficiency and quality of the processing link, and then extending to the circulation link, through blockchain, traceability technologies, and supply chain transparency measures to improve logistics efficiency and the consumer experience in the terminal market. Vertical diffusion can significantly enhance the technical application level of each link within the value chain, promoting closer technical collaboration and data sharing among links. However, the success of vertical diffusion is highly dependent on whether effective technical interfaces and data sharing mechanisms can be established between different links, and insufficient collaboration between links will lead to the obstruction of vertical diffusion, reducing the effectiveness of technology application.

Horizontal diffusion is the dissemination and sharing of technology among different entities within the same level of the value chain. It mainly involves the empowerment of technology-lagging entities (such as small and medium-sized farmers or cooperatives) by leading entities (such as Leading enterprise or digital platforms)[2]. The success of horizontal diffusion depends on whether advanced entities can effectively output technology, provide resource support, training, and consultation services to lagging entities to help them break through constraints such as funds, infrastructure, and technological cognition. However, horizontal diffusion often faces acceptance barriers for lagging entities due to lack of funds, insufficient cognition, or weak infrastructure. The degree of collaboration between entities, the sufficiency of information sharing, and the level of trust also deeply affect the actual effect of horizontal diffusion. Insufficient collaboration or unreasonable benefit distribution mechanisms often lead to unsatisfactory results in horizontal diffusion.

In conclusion, the complexity of the technology diffusion process stems from the structural differences in technical capabilities, resource endowments, and infrastructure conditions among different entities. These differences significantly affect the efficiency and coverage of technology dissemination, resulting in a clear imbalance in technology diffusion in practice. To deeply explore the intrinsic mechanism of technology diffusion and its systematic role in the digitalization process of the agricultural value chain, the next step will be to construct a technology diffusion model based on the theory of dynamic systems. Through mathematical methods, the dynamic paths of technological level evolution among multiple entities will be depicted, the enabling logic of the leading technology entity to the relatively lagging entity will be explained, and the relevant influences of key parameters such as diffusion efficiency and connection strength on the diffusion effectiveness will be analyzed.

3.3 Model Construction and Analysis

Under the framework of the technology diffusion theory, this paper constructs a differential equation model to depict the dynamic evolution process of technological levels in a multi-agent system, and to reveal the internal mechanism of how the technological levels of the agents change over time. Technological progress is not only limited by the technological decline trend of the agents themselves, but is also influenced by the technological gap between them and the connection strength. The dynamic function of the technological level of the agent is expressed as:

$$\frac{dT_i(t)}{dt} = a\sum w_{ij}\left(T_j(t)\text{-}T_j(t)\right) - \beta T_i(t) \tag{1}$$

In Formula (1), TitTit represents the technological level of agent ii at time tt. wijwij denotes the connection strength between agents ii and jj, measuring the degree of their interaction in information sharing, technical collaboration, and other aspects. The parameter aa is the technology diffusion efficiency coefficient, reflecting the speed at which technology spreads from one agent to another. The parameter ββ represents the technology decay coefficient, reflecting the tendency of technology to weaken over time in application. The core driving force of technology diffusion stems from the technological gap between agents Tjt−TitTjt−Tit and their connection strength wijwij. When the technological gap is large, technologically advanced agents have a more significant driving effect on technologically lagging agents, meaning that higher connection strength helps improve the speed and quality of technology transmission. The term βTitβTit reflects the endogenous trend of technology decay, constituting an important variable that cannot be ignored in the dynamic evolution of technology.

To characterize the mechanism of policy intervention in the technology diffusion process, policy variables with moderating effects are further introduced, mainly including the subsidy term PaPa targeting technology diffusion efficiency and the incentive term PwPw for collaborative relationships among agents. The former reflects the government's efforts to enhance the efficiency of technology transmission through measures such as increasing technical training and equipment subsidies. The latter manifests as strengthening cooperative relationships among multiple agents through institutional arrangements or resource support. After introducing policy factors, the model is revised as:

$$\frac{dT_i(t)}{dt} = \left(a+P_a\right)\sum w_{ij}\left(1+P_w\right)\cdot\left(T_j(t)\text{-}T_j(t)\right) - \beta T_i(t) \tag{2}$$

Here, PaPa is the direct subsidy for technology diffusion efficiency, and PwPw is the policy incentive for the connection strength between agents. An increase in both can significantly enhance the efficiency of technology transmission and the level of synergy among agents at the mechanism level, thereby effectively accelerating the overall process of technology diffusion. The dual promoting effect of policy intervention on technology diffusion is twofold: on one hand, directly improving the diffusion efficiency a+Paa+Pa can shorten the time required for technology transmission and increase the transmission rate. On the other hand, by enhancing the connection strength wij1+Pw1+Pwwij, it expands the scope and depth of technology transmission, helping to strengthen knowledge flow and capability sharing among multiple agents. Based on the above model, the following conclusions are drawn:

First, technology diffusion efficiency aa and the connection strength wijwij between agents are the two core parameters determining the effectiveness of diffusion. Diffusion efficiency reflects the speed and effectiveness of technology transmission between different agents, while connection strength measures the closeness of collaborative relationships. When the collaborative relationship between technologically advanced agents and relatively lagging agents is stable, the speed and coverage of technology diffusion will be significantly enhanced, thereby promoting technological balance and synergistic upgrading across different links of the value chain. In scenarios with high diffusion efficiency, agents at a technological disadvantage can also more quickly bridge the technology gap and enhance overall competitiveness.

Second, policy intervention plays a significant role in accelerating and guiding the technology diffusion process.

While improving technology diffusion efficiency and the connection strength between agents, it effectively drives the system's overall technological level toward a higher-quality long-run equilibrium state. Under steady-state conditions, the technological level of agent ii can be expressed as:

$$T_i^* = \frac{\left(a+P_a\right) \Sigma\, w_{ij} \left(1+P_w\right) T_j^*}{\beta+\left(a+P_a\right) \Sigma\, w_{ij} \left(1+P_w\right)} \tag{3}$$

From (3), it can be seen that an increase in the policy variables (Pa,Pw)(Pa,Pw) significantly enhances the long-run equilibrium technological level of technologically lagging agents, effectively shortens the time required for technology diffusion, and increases the system's convergence speed. Furthermore, the closeness of collaborative relationships among agents has a significant impact on the effectiveness of technology diffusion; the higher the connection strength, the greater the scope and depth of diffusion, providing a solid theoretical basis for the path selection and key areas of policy intervention.

Third, the practical implication of the technology diffusion model is that, in addressing real-world challenges such as weak technology adoption capacity among smallholder farmers and limited access to information channels, the government can improve the efficiency and breadth of technology transmission at the mechanism level by increasing technology extension subsidies PaPa or enhancing incentives PwPw for collaboration between leading enterprises and smallholder farmers. This can effectively accelerate the digitalization process across all links of the agricultural value chain. Thus, the technology diffusion mechanism not only constitutes an important driving force for empowering the upgrading of the agricultural value chain through new quality productive forces but also provides theoretical support for building a highly efficient, synergistic, and fully covered modern agricultural system. The multiplier effect of policy intervention further strengthens the overall performance of technology diffusion, offering institutional guarantees and practical pathways for advancing agricultural modernization and achieving high-quality development.

4. Policy Recommendations

The above two parts, from the perspectives of theoretical explanation and model construction, elaborated on the internal logic and dynamic structure of how new quality productive forces can drive the digital transformation of the agricultural value chain through the mechanism of technology diffusion, and clarified the endogenous evolutionary path of agricultural digitalization development. It can be seen that new quality productive forces, with their technological penetration, data-driven nature, and network collaboration among entities, have become the key driving force for achieving digital transformation in the agricultural value chain. On one hand, new quality productive forces promote the systematic penetration of digital technologies along each link of the agricultural value chain through vertical diffusion; on the other hand, they enhance the enabling effect of leading technology entities on technology-lagging entities through horizontal diffusion, effectively bridging the technological gap among entities and stimulating the inherent growth potential of the value chain as a whole.

To further enhance the promoting effect of new quality productive forces on the digital transformation of the agricultural value chain, policy formulation should coordinate efforts in three dimensions: technology promotion, factor optimization, and platform construction. Following the principles of systematicness and coordination, a multi-level comprehensive policy system should be constructed. Specifically, efforts should be made to improve the efficiency of digital technology diffusion, strengthen the infrastructure construction of agricultural data and other factors, optimize the mode of agricultural resource allocation, actively build a digital platform ecosystem, and promote in-depth collaboration among multiple entities to effectively promote the comprehensive and in-depth development of the digitalization of the agricultural value chain, laying the foundation for agricultural modernization and the sustainable development of the agricultural economy.

4.1 Technology Promotion and Enhancement of Technology Diffusion Efficiency

The effective diffusion of digital technology is an important support for the digital transformation of the agricultural value chain. However, there are significant differences in the adoption of technology among entities in the current technology diffusion process, especially among relatively backward entities represented by small and medium-sized farmers and cooperatives, who face practical problems such as financial constraints, lack of technical knowledge, and insufficient infrastructure, and are unable to fully participate and effectively apply digital technology. Therefore, policy intervention needs to focus on reducing the threshold for technology adoption, strengthening the extensive dissemination of technology among different agricultural entities through targeted equipment subsidies, training programs, and collaboration network construction. Specifically, the government can formulate precise subsidy policies for precision agricultural equipment (such as drones, IoT sensors, and intelligent irrigation systems) to help technology-lagging small and medium-sized entities reduce the economic cost of technology adoption. At the same time, the agricultural technology promotion department and professional training system should be enhanced to improve the digital technology application capabilities of farmers and cooperatives. It is also necessary to actively promote the establishment of technology collaboration networks between leading enterprises and small and medium-sized farmers, through mechanisms such as technology demonstration, knowledge sharing, and capacity output, to effectively bridge the technological gap among entities and promote the coordinated development of technology diffusion.

4.2 Optimization of Factors and Construction of Data Infrastructure

Data, as the core production factor of digital technology application, plays a fundamental role in the digital transformation of the agricultural value chain. However, the high cost of data collection, analysis, and sharing significantly restricts the popularization and in-depth application of data factors among agricultural entities, especially small and medium-sized entities. Therefore, accelerating the construction of data infrastructure and reducing the cost of data acquisition and use have become important policy directions for optimizing agricultural resource allocation and improving the operational efficiency of the agricultural value chain. The government should increase investment in IoT infrastructure in the agricultural sector, through large-scale deployment of soil environment sensors, real-time monitoring equipment, and intelligent production management systems, to provide real-time data support for agricultural production decisions. At the same time, a unified agricultural data sharing platform should be constructed to break the status quo of "data islands" among various entities, and promote the coordinated development of agricultural entities through a standardized data sharing mechanism. The government should also actively formulate incentive policies to encourage agricultural entities to widely apply data-driven decision-making tools such as market forecasting, production optimization, and intelligent supply chain. This will promote the deep integration of data with traditional production factors such as land, capital, and labor, enhance the overall operational efficiency of the agricultural value chain, and stimulate the internal driving force for agricultural digital transformation[4].

4.3 Construction of Digital Platforms and the Establishment of Collaborative Ecosystems

Digital platforms serve as crucial hubs for integrating agricultural value chain resources and facilitating entity collaboration. They play a key role in driving agricultural digital transformation. The platform model effectively improves the operational efficiency of the agricultural value chain and the collaboration level among multiple entities through the integration of upstream and downstream resources, information sharing, and network collaboration. Therefore, the government should focus on the cultivation and optimization of digital platforms to promote the establishment of an agricultural digital ecosystem dominated by platform economy. On one hand, it should vigorously support the construction of agricultural e-commerce, supply chain finance, and agricultural service platforms, especially in areas where small and medium-sized farmers and agricultural cooperatives are under-represented, to accelerate the promotion of platform services and reduce the barriers for technology-poor entities to integrate into the digital value chain, helping them easily access market information, financing channels, and technical support. On the other hand, it should promote the standardization and interconnection of cross-platform data, through policy guidance to establish data sharing mechanisms and cooperation networks among platforms, breaking the data barriers between platforms and releasing the resource integration and network collaboration effects of platform economy. It should also encourage digital platforms to innovate in technology research and service models, developing precise agricultural solutions such as intelligent agricultural equipment scheduling, pest and disease intelligent monitoring and prediction tools, and supply chain intelligent management systems, deepening the collaboration between platforms and value chain entities. Policies need to ensure the openness and inclusiveness of platforms, providing access opportunities for more small and medium-sized farmers and cooperatives, and forming a wide-ranging and closely-coordinated agricultural digital ecosystem.

5. Conclusion

The role of new quality productive forces in the digitalization process of the agricultural value chain is not only reflected in the effective improvement of agricultural production efficiency and resource allocation levels, but also in the promotion of the transformation of the entire agricultural economy towards an intelligent, ecological and sustainable development model. From the perspective of practical approaches, new quality productive forces rely on digital technology and, through the diffusion mechanisms in both vertical and horizontal dimensions, accelerate the dissemination and application of technology among all links and entities in the agricultural value chain, promoting the comprehensive digital upgrade of the agricultural industry. Since the efficiency of technology diffusion and the tightness of the collaboration network among entities constitute the core elements determining the effectiveness of diffusion, policy intervention plays a crucial regulatory role in enhancing the efficiency of technology diffusion and strengthening collaboration among entities. Through the coordinated effect of a series of measures such as precise subsidies for technology promotion implementation, accelerating the construction of agricultural data infrastructure, and promoting the construction of digital platform ecosystems at the policy level, the technological gap among entities is effectively narrowed, technology is fully penetrated in the agricultural value chain, and the overall efficiency of the agricultural value chain and the sustainable development level are continuously enhanced. In the following research and practice, it is necessary to combine the characteristics of different industries and regional differences to explore diverse implementation paths for new quality productive forces to empower the digital transformation of agriculture, providing more abundant theoretical foundations and practical experiences for promoting the modernization of agriculture in China.

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