Journal of Trends in Financial and Economics
Print ISSN: 3007-6951
Online ISSN: 3007-696X
DOI:https://doi.org/10.61784/jtfe3051

EMPOWERING THE ENTIRE AGRICULTURAL VALUE CHAIN WITH DIGITAL TECHNOLOGIES: A MECHANISM STUDY ON DRIVING LEAPS IN NEW QUALITY AGRICULTURAL PRODUCTIVITY

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Abstract: In the context of the information age, digital technology is profoundly empowering the entire agricultural value chain, driving a qualitative leap in agricultural productivity across production, processing, circulation, and sales. This paper first constructs a theoretical framework for digital agriculture, systematically outlining the application pathways of key technologies such as the Internet of Things, big data, artificial intelligence, and blockchain in monitoring the agricultural production environment, precision irrigation and fertilization, pest and disease prediction and control, intelligent processing and quality traceability, cold chain logistics optimization, and precision marketing and interaction. Secondly, through typical cases, it verifies the significant effects of digital technology on indicators such as water saving, pesticide reduction, loss reduction, lower defect rates, reduced spoilage rates, and lower transportation costs. Finally, based on four mechanisms—technological innovation, data-driven decision-making, industrial chain synergy, and market responsiveness—it proposes policy recommendations for building rural networks and big data platforms, strengthening talent cultivation and recruitment, increasing special funds and financial support, improving standards and data security, and promoting industrial synergy. This research provides theoretical support and practical pathways for the digital transformation and high-quality development of agriculture.
Keywords: Digital technologies; Entire agricultural value chain; New quality agricultural productivity; Industrial synergy; Policy framework

1 INTRODUCTION

In today's information age, the rapid advancement of digital technology is profoundly reshaping the global economic structure, particularly in traditional sectors like agriculture. The relationship between digitalization and agricultural development has grown increasingly close, not only revolutionizing agricultural production but also injecting new vitality into the entire value chain from production to consumption. By enhancing production efficiency, optimizing resource allocation, and strengthening market competitiveness, the application of digital technology is driving a qualitative leap in agricultural productivity. As a major agricultural nation, China has consistently prioritized agricultural modernization in its national development. Driven by digitalization, Chinese agriculture is undergoing a profound transformation. The application of digital technology has expanded from isolated production segments to the entire value chain, encompassing crop cultivation, animal husbandry, processing, logistics, and sales. First, in agricultural production, technologies like smart agriculture and precision agriculture leverage IoT, big data, and cloud computing to enable real-time monitoring and intelligent regulation of crop growth environments, effectively increasing yields and quality. Second, in processing and logistics, digital applications improve efficiency, accelerate logistics, reduce costs, and ensure product quality. In sales, the rise of e-commerce platforms and social media has opened broader markets for agricultural products and enhanced their competitiveness. Despite notable achievements, gaps persist compared to developed countries. China's agricultural digital infrastructure remains underdeveloped, technology penetration is low, and digital integration across the industry chain remains fragmented—all constraining agricultural modernization. Therefore, this paper aims to explore how digitalization empowers the entire agricultural value chain and proposes pathways to drive a new qualitative leap in productivity. Theoretically, it enriches the framework of agricultural modernization and digital empowerment by analyzing how digital technologies embed into the value chain, offering new perspectives and empirical evidence. Practically, it provides actionable insights for China's agricultural digital transformation, serving as a reference for policymakers and agribusinesses. By identifying key empowerment mechanisms and drivers, this study offers theoretical and practical support for achieving high-quality agricultural advancement, thereby accelerating industrial upgrading and contributing to rural revitalization.

2 THEORETICAL FRAMEWORK AND VALUE CHAIN SYSTEM OF DIGITAL AGRICULTURE

2.1 Theoretical Basis of Digital Empowerment in Agriculture

2.1.1 Application theories of digital technology in agriculture

The Internet of Things (IoT) employs various information sensors, RFID, GPS, infrared sensors, laser scanners, and other devices to collect real-time data—such as sound, light, heat, electricity, mechanical force, chemistry, biology, and location—from objects or processes requiring monitoring, connection, or interaction. By enabling ubiquitous connectivity between objects and humans through diverse networks, IoT achieves intelligent perception, identification, and management. In agriculture, IoT facilitates real-time monitoring of the production environment. For example, deploying temperature-humidity sensors, light sensors, and soil moisture sensors in greenhouses captures environmental parameters and transmits them to control centers. Farmers can remotely regulate ventilation and irrigation systems based on this data, enabling precision agricultural management. Additionally, IoT supports product traceability. Electronic tags record information across planting, breeding, processing, and logistics stages, allowing consumers to scan labels for detailed product information, thereby enhancing trust in quality.

Big data refers to massive, high-growth, diversified information assets that cannot be captured, managed, or processed by conventional software within a specific timeframe, requiring new processing models to enhance decision-making, insight discovery, and process optimization. In agriculture, big data integrates production, market, weather, and other datasets. Analyzing production data—such as soil fertility and crop growth cycles—provides precise fertilization and irrigation recommendations, boosting yield and quality. Market data analysis helps farmers understand demand and price trends, optimizing planting and breeding plans to avoid overproduction. Meteorological big data enables early disaster warnings, allowing preemptive measures to minimize losses.

Artificial intelligence (AI) is a technological science focused on developing theories, methods, and applications to simulate and extend human intelligence. In agriculture, AI is primarily applied to image recognition and robotics. Agricultural image recognition analyzes crop images to identify pests, diseases, and growth status. For instance, deep learning algorithms can diagnose infected leaves and determine pathogen types, offering targeted control strategies. Agricultural robots perform repetitive or labor-intensive tasks—such as fruit picking and weeding—using advanced sensors and AI algorithms to autonomously recognize crops and environments, efficiently executing production tasks.

Blockchain is a distributed, shared ledger and database characterized by decentralization, immutability, traceability, collective maintenance, and transparency. In agriculture, it ensures quality traceability and supply chain management. Blockchain records immutable, traceable data from production to consumption. Consumers scan QR codes to access details on farming practices, pesticide/fertilizer use, and logistics, guaranteeing product safety. For supply chains, blockchain enhances transparency and efficiency, reduces fraud, and lowers transaction costs.

2.1.2 Impact of digital technology on agricultural value chain segments

Digital technology has enabled more precise and intelligent agricultural production. Traditional farming often relies on experiential practices for fertilization and irrigation, leading to resource waste and environmental pollution. Applications like IoT and big data now enable real-time monitoring of soil fertility and moisture levels, allowing precise delivery of nutrients and water based on crop needs to enhance resource efficiency. Meanwhile, AI and agricultural robots reduce labor dependency while improving productivity and quality. For example, large-scale farms deploy robots for seeding and weeding, achieving high-speed, high-precision operations that ensure crop growth quality. Digital tools also facilitate early pest/disease detection and control, minimizing yield and quality losses.In processing, digital technology automates and intellectualizes production. IoT monitors equipment parameters (e.g., temperature, pressure) in real time, triggering alerts and corrective actions for anomalies[1]. Big data analytics optimize processing techniques by analyzing batch data—identifying ideal parameters to improve product texture and quality. Blockchain records immutable processing data, ensuring transparency and traceability to boost consumer trust.For circulation, digital solutions optimize logistics and supply chains. IoT enables real-time monitoring of transport conditions (e.g., temperature/humidity in cold-chain vehicles) to preserve product quality. Big data analyzes market demand and logistics patterns, optimizing distribution routes and inventory management—reducing spoilage and costs by aligning supply with regional demand. Blockchain enhances supply chain transparency and trust, lowering transaction costs through shared, tamper-proof records of every transfer. Figure 1 illustrates the mechanism through which digital technology empowers new qualitative leaps in agricultural productivity.

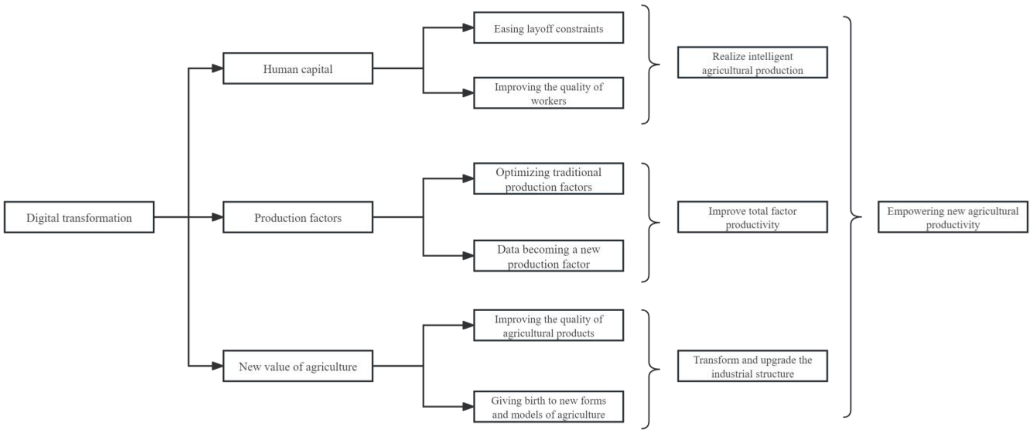

Figure 1 The Mechanism of Digital Transformation Empowers New Agricultural Productivity

Digital technology has introduced new models and channels for agricultural product sales. The rise of e-commerce platforms enables farmers to directly reach consumers nationwide and globally, expanding market access. Through online platforms, farmers can showcase products, communicate directly with consumers to understand preferences and feedback, and promptly adjust production and sales strategies. Simultaneously, big data technology analyzes consumer purchasing behavior and preferences to develop precision marketing strategies—for instance, recommending products aligned with tastes based on purchase history and search records. Emerging models like livestream commerce have also rapidly developed through digital means, leveraging host demonstrations to enhance sales effectiveness.In summary, the application of digital technology in agriculture rests on a solid theoretical foundation and profoundly impacts every segment of the agricultural value chain. These effects enhance production efficiency, improve product quality, reduce costs, and propel agriculture toward modernization and intellectualization.

2.2 Concept and Composition of the Entire Agricultural Value Chain

The entire agricultural value chain in agriculture refers to a collection of interconnected and interdependent value-creation activities spanning from the input of agricultural production materials through the production, processing, and circulation of agricultural products until the final sale to consumers. It transcends the mere physical flow of products "from farm to table," encompassing a multidimensional complex system involving information transfer, capital flow, and value addition. Emphasizing the holistic and systemic nature of the agricultural industry, it treats all production segments as an organic whole where each stage impacts the final product's value. By integrating these segments, resources can be optimally allocated, agricultural productivity enhanced, and product value increased—ultimately strengthening the competitiveness and economic returns of the entire agricultural sector. Compared to traditional agricultural supply chains, the entire value chain prioritizes synergistic development and co-creation of value across stages. It addresses not only production and sales but also pre-production activities (e.g., input supply, R&D), mid-production management (e.g., cultivation, breeding), and post-production processes (e.g., processing, packaging, logistics, marketing). Simultaneously, it centers on consumer demand and preferences, enabling market-oriented, differentiated, and personalized production to meet diverse needs[2].

The production segment forms the foundation of the entire agricultural value chain, directly determining the quantity and quality of agricultural products. This stage involves inputs such as seeds, fertilizers, pesticides, and machinery, alongside applied technologies like cultivation, breeding, and irrigation techniques. Producers select crop or livestock varieties based on market demand and natural conditions, implementing scientific management practices. Emphasis is placed on ecological sustainability—adopting green and organic methods to reduce chemical inputs while enhancing product quality and safety. Modern technologies like IoT and big data enable intelligent, precision management to boost efficiency and resource utilization. Processing serves as the key value-adding stage, transforming products' form, function, and shelf life to increase their worth. It includes two tiers: primary processing (cleaning, grading, packaging) to preserve freshness and facilitate storage/transport, and deep processing (extraction, concentration, fermentation) to yield high-value outputs like foods, beverages, and nutraceuticals. Innovation in technology and equipment is essential to improve quality, with stringent safety controls ensuring regulatory compliance. Circulation bridges production and consumption, enabling spatial transfer and temporal adjustment of products through procurement, transportation, storage, and distribution. Procurement involves contractual agreements between producers and brokers/traders. Transportation modes (road, rail, water, air) are selected based on product characteristics and distance to ensure safety and timeliness. Storage utilizes modern facilities for preservation and supply regulation, while distribution employs efficient logistics to deliver products to retailers, markets, and food service providers. Innovations like e-commerce and cold-chain logistics expand market reach through online-offline integration. Sales, the final stage, determines market value and economic returns. Strategies are tailored to consumer preferences via traditional channels (supermarkets, wholesale markets—broad coverage, high trust) and emerging channels (e-commerce, community group buying, livestream sales—speed, cost-efficiency, interactivity). Brand building and marketing enhance visibility and competitiveness. Additionally, the value chain includes pre-production segments (input supply, R&D) providing essential materials and technological support, and post-production segments (after-sales service, consumer feedback) enabling continuous optimization through demand insights.

2.3 Current Research Status of Digital Empowerment in Agricultural Value Chains: Domestic and International Perspectives

International scholars have focused earlier on applying digital technologies in agricultural production. Precision agriculture represents a key research area, with numerous studies concentrating on technologies like satellite remote sensing, Geographic Information Systems (GIS), and Global Positioning Systems (GPS). Smith notes that satellite remote sensing enables real-time monitoring of soil moisture and crop growth, assisting farmers in precise fertilization and irrigation to enhance efficiency and resource utilization [3]. Additionally, sensor technology has been extensively studied; sensors installed on machinery or livestock collect environmental parameters and animal health data in real time, supporting intelligent production decisions.

In agricultural circulation, digital technologies primarily optimize supply chain management and product traceability. International scholars emphasize blockchain's role in traceability, enabling end-to-end information recording and sharing to improve supply chain transparency and credibility. Jones' research demonstrates blockchain's effectiveness in addressing quality safety issues and strengthening consumer trust. Simultaneously, IoT technology is widely adopted for monitoring temperature and humidity during logistics, ensuring product quality and freshness.

Some scholars explore digitalization's impact on agricultural value chain integration. Digital technologies facilitate information sharing and collaboration among agribusinesses, breaking down information silos between traditional value chain segments. Brown's study finds that digital platforms enable tighter integration among production, processing, and sales entities, allowing resource sharing and complementary advantages to boost overall competitiveness [4]. To reflect global prioritization of smart agriculture, key recent initiatives or legislation from Japan, the EU, and the US are briefly summarized in Table 1.

Table 1 Important Bills or Plans Related to Smart Agriculture in Europe, America and Japan in Recent Years

Country/Organization	Important bills or plans related to smart agriculture	Content related to smart agriculture
USA	Agriculture Improvement Act Precision Agriculture Connectivity Act Agricultural Innovation Agenda Sustained Agricultural Research and Education Act	Approved by the U.S. Congress on December 20, 2018, and implemented by the U.S. Department of Agriculture (USDA); emphasizes the application of agricultural technology and data management, promotes the research and development of smart agriculture and precision agriculture technology. As part of the 2018 Agriculture Improvement Act, it aims to promote high-speed Internet coverage of U.S. farmland and support the technical needs of smart agriculture, such as data collection, analysis and instant decision support. Launched by the USDA in February 2020, it aims to stimulate innovation in the agricultural sector, including by improving resource utilization efficiency, promoting the development of precision agriculture and smart agriculture technology, and promoting the sustainability of agriculture through science and technology, including the practice of smart agriculture, such as using big data and AI to optimize resource utilization and production efficiency.
European Union	European Green Deal Common Agricultural Policy (CAP) 2021-2027 EU Digital Agriculture Strategy	On December 11, 2019, the European Commission proposed that smart agriculture be included in the discussion as part of achieving a sustainable food system, aiming to improve agricultural efficiency and reduce environmental impact through technology and innovation. This policy covers a wide range of agricultural topics, but one of the focuses is smart agriculture and digital transformation, encouraging the use of advanced technologies and practices to improve agricultural sustainability and competitiveness. The EU Research and Innovation Framework Program, launched in 2021, provides funding for smart agriculture to support research and innovation in related fields. It aims to promote policy formulation and investment related to smart agriculture.
Japan	"Society 5. 0" strategy Ministry of Agriculture, Forestry and Fisheries' smart agriculture promotion plan Agricultural production base strengthening plan Agricultural Comprehensive Strategy (2020 edition）	Smart agriculture is seen as a key part of achieving efficient and sustainable agricultural production in the Society 5.0 strategy. It aims to improve agricultural productivity and domestic agricultural competitiveness by utilizing advanced technologies such as ICT (information and communication technology), big data and artificial intelligence. The Japanese government released it on December 10, 2019. It aims to strengthen the foundation of agricultural production and promote the development of smart agriculture, including the implementation of smart agriculture and the promotion of digital policies. It also promotes a number of measures to promote smart agricultural solutions, including encouraging innovation, providing financial support and simplifying the regulatory framework to promote the deployment of new technologies and services.

Since 2019, China has successively issued the *Digital Rural Development Strategy Outline*, the *"14th Five-Year Plan" for Digital Economy Development*, the *Digital Agriculture and Rural Development Plan (2019–2025)*, and the *Digital Rural Development Action Plan (2022–2025)*, vigorously promoting smart agriculture, digital agriculture, and digital rural construction from the policy level to accelerate digital transformation in agriculture and rural areas. Domestic scholars have also extensively researched the application of digital technologies across agricultural segments. The formation and development of new qualitative productive forces in agriculture not only effectively overcome inherent agricultural vulnerabilities (Gong Binlei, Yuan Lingran, 2024)but also serve as a critical pathway to common prosperity for farmers[5]. As agricultural digitalization advances, it significantly reshapes the material and social attributes of these new productive forces (Gao Yuan, Ma Jiujie, 2024)[6], directly impacting total factor productivity (TFP). By facilitating revolutionary technological breakthroughs, innovative factor allocation, and industrial transformation, agricultural digitalization substantially enhances TFP through increasing the marginal returns of agricultural inputs[7]. This positions digital transformation as a key driver for developing new agricultural productive forces, profoundly influencing common prosperity via rural economic growth (You Liang, Tian Xiangyu, 2024)[8]. In production, AI aids crop disease/pest diagnosis and prediction; image recognition enables rapid, accurate identification, providing timely control advice while reducing pesticide use and improving product quality. In circulation, e-commerce platforms create new sales channels, eliminating intermediaries and raising farmer income while expanding market reach and fostering brand development. Domestic research also explores pathways for digital empowerment of agricultural value chain upgrading. Studies propose establishing digital agricultural platforms to integrate resources and enable synergistic development, requiring collaborative efforts among government, enterprises, and farmers. Digital finance is recognized as vital for providing financing support. Additionally, digital technologies reshape relationships among value chain actors: digital platforms foster stable "contract farming" partnerships between cooperatives and processors, enhancing farmer organization and bargaining power. Despite progress, research gaps persist. Most studies focus on isolated segments rather than systemic integration across the entire chain (e.g., seamless coordination from production to sales). Performance evaluation remains understudied, lacking robust metrics to quantify economic, social, and ecological impacts (e.g., precise contributions to efficiency gains or farmer income). Emerging risks (cybersecurity, data privacy) and mitigation strategies are inadequately addressed. Regional disparities in development levels, infrastructure, and policy contexts—affecting digitalization outcomes—require further comparative analysis to inform tailored strategies.

3 ANALYSIS OF PATHWAYS FOR DIGITAL EMPOWERMENT IN THE ENTIRE AGRICULTURAL VALUE CHAIN

3.1 Digital Applications in Production

In agricultural production, digital technologies such as IoT and big data play pivotal roles, driving transformative changes that significantly enhance efficiency and quality. IoT enables real-time soil moisture monitoring through field-deployed sensors. Data transmitted to smart control systems trigger automatic irrigation based on preset thresholds. For instance, in wheat fields, the system activates irrigation when moisture falls below optimal levels, enabling precise water supplementation. This approach prevents over-irrigation (reducing water waste and soil degradation) and under-irrigation (avoiding growth impairment), ensuring optimal hydration across growth stages to boost yield and quality while maximizing water-use efficiency.

In greenhouse cultivation, IoT monitors and auto-adjusts temperature, humidity, light, and CO_2 concentration. For example, in smart flower greenhouses, sensors trigger ventilation/shading when temperatures rise or CO_2 generators when levels drop, maintaining stable conditions that minimize pest incidence, accelerate growth, and enhance quality—resulting in brighter, longer-lasting blooms with higher market value.

In livestock farming, IoT-enabled wearables (collars, ear tags) track physiological indicators like body temperature and activity. Abnormalities trigger alerts for immediate intervention. For instance, detecting elevated temperature and reduced mobility in cattle allows prompt treatment, curbing disease spread, lowering mortality, and raising profitability[9].

Production Decision Support: Big data integrates meteorological, soil, and crop growth data to provide scientific guidance. Analyzing historical climate and yield data predicts optimal planting times and varieties regionally. For maize cultivation, it recommends suitable hybrids and practices based on local conditions, boosting yield and quality. Market trend analysis also helps farmers align planting plans with demand to avoid oversupply.

Pest/Disease Prediction and Control: Big data constructs predictive models using historical pest data, weather patterns, and crop growth stages. Early warnings enable targeted interventions—e.g., forecasting outbreaks allows farmers to prepare pesticides and equipment, reducing crop damage, chemical usage, and safety risks.

Quality Traceability: Big data establishes traceability systems documenting inputs (fertilizers, pesticides, feed), harvesting, processing, and logistics. Consumers scan QR codes to access full lifecycle information, enhancing transparency and trust while incentivizing producers to prioritize safety.

In summary, IoT and big data technologies deliver multifaceted benefits: heightened efficiency, reduced costs, improved quality, and sustainable modernization.

3.2 Digital Upgrading in Processing

Automated equipment and robots are proliferating in processing. In fruit sorting, machines use cameras and AI to rapidly classify by size, color, and shape, removing substandard produce to ensure uniform quality—increasing efficiency while reducing human error and damage. In meat processing, robots execute precise cutting/packaging tasks under preset parameters, ensuring consistency and operating reliably in harsh environments to reduce labor hazards.Digital technologies enable real-time production monitoring and optimization. Sensors on assembly lines track temperature, humidity, pressure, and flow rates. Data feeds into control systems where managers oversee operations via dashboards. Deviations trigger automatic alerts and adjustments—e.g., in winemaking, precise environmental control during fermentation enhances flavor. Data analytics further identifies process improvements to boost efficiency and quality[10].

Blockchain provides reliable quality traceability. Each processing step—from raw material procurement to finished goods—is immutably recorded. Batch-specific QR codes allow consumers to access details like ingredient origins, processing logs, and test reports. This transparency builds trust and enables rapid issue tracing.

Digital tools revolutionize food safety testing. Spectral analysis rapidly detects pesticide residues and heavy metals by analyzing light signatures, replacing slow traditional methods. IoT-based monitoring systems deploy sensors across facilities to track temperature, humidity, and microbial levels in real time, triggering instant alerts for anomalies.Big data analytics uncover market trends and consumer preferences. By studying purchase records, social media, and surveys, processors identify unmet needs—e.g., demand for low-sugar or high-fiber foods—guiding R&D and recipe optimization. Customization also thrives: direct consumer engagement enables personalized products (e.g., bespoke juice blends), supported by agile digital production systems that ensure quality and delivery timelines.Digital platforms facilitate supply chain collaboration. Shared management systems synchronize real-time data on material supply, production progress, and inventory among processors, suppliers, and distributors. For instance, predictive procurement orders align with production schedules, while sales monitoring informs inventory adjustments, enhancing flexibility.

Smart logistics amplify product value. IoT tracks vehicle location, speed, and cargo conditions in transit, enabling dynamic routing. Automated warehousing employs robots for efficient storage/retrieval and adjusts environmental parameters (temperature/humidity) to preserve quality, minimizing handling errors and costs.

3.3 Digital Optimization of Distribution Links

3.3.1 Digital integration of the agricultural products supply chain

Build a digital information–sharing platform covering all links of agricultural products production, processing, transportation, and sales. On the production side, farmers can upload planting information such as planting dates, fertilizer and pesticide usage, and estimated yields; processing enterprises can display their processing capacity and product types on the platform; logistics companies can provide real-time data on vehicle locations and transport capacity. Through this platform, all participants can obtain the information they need in real time, achieving coordinated operation of the supply chain. For example, retailers can use the platform’s production progress and transportation status of agricultural products to plan replenishment in advance, reducing stock-out incidents. By applying big-data analytics to deeply mine the platform’s information, one can analyze sales trends and price fluctuation patterns of agricultural products, providing decision support for farmers and enterprises. For instance, by analyzing historical sales data to forecast market demand for a particular agricultural product over a future period, farmers can adjust planting scale and varieties according to the forecast, avoiding overproduction and unsold inventory. Introduce blockchain technology to ensure the authenticity and traceability of agricultural product circulation information[11]. From the source of the products onward, every link’s information is recorded on the blockchain; consumers can scan a QR code on the product to query detailed information on origin, production process, and transportation path, enhancing trust in product quality. At the same time, blockchain technology aids regulatory authorities in supervising product quality; once an issue is detected, it can be traced back to the source swiftly. Achieve automated operations across supply-chain links. For example, in warehousing, adopt automated storage systems to automatically store and retrieve goods, improving warehouse utilization and inbound/outbound efficiency. In transportation, use intelligent dispatch systems that automatically plan optimal transport routes based on cargo volume, destination, and vehicle locations, reducing transport costs and time.

3.3.2 Digital upgrade of logistics and distribution

Employ Internet of Things technology to realize intelligent warehouse management. Install various sensors in warehouses to monitor temperature, humidity, and storage status of goods in real time. When environmental parameters exceed set ranges, the system automatically issues alerts and takes corrective measures to ensure storage quality of agricultural products. For perishables requiring cold storage, sensors monitor temperature to keep it within appropriate ranges. Adopt a Warehouse Management System (WMS) for refined management of warehouse operations. A WMS can automate inbound, outbound, and inventory operations, improving accuracy and efficiency. It can also interface with the supply-chain information-sharing platform for real-time inventory updates, allowing all parties to grasp stock levels promptly. Promote the use of smart transport equipment, such as vehicles equipped with GPS and sensors. Through GPS, logistics companies can track real-time vehicle locations and driving status, optimizing routes and boosting efficiency. Sensors monitor speed, load, and cargo condition to ensure safety and quality; for example, if a vehicle speeds or cargo vibrations exceed thresholds, the system alerts operators. Develop digital monitoring for cold-chain logistics. For perishable goods transport, establish a cold-chain logistics monitoring platform to track temperature and humidity of transport equipment in real time. If temperatures deviate, the platform immediately notifies relevant personnel to take action, ensuring quality and safety during transport. Meanwhile, use big-data analytics on cold-chain operation data to optimize transport schemes and reduce costs.

3.3.3 Digital expansion of agricultural products sales channels

Encourage farmers and agri-enterprises to join e-commerce platforms and open online stores, broadening sales channels. E-commerce offers vast reach and low sales costs, allowing products to reach national or even global markets. Platforms also provide data-analysis services to help farmers and enterprises understand consumer demand and preferences, optimizing sales strategies. Use live-streaming to promote sales: invite influencers or product ambassadors to livestream, showcasing product features, origin environment, and production process to attract viewers and purchases. Live-streaming enables real-time interaction, answering consumer questions to boost purchase intent. For example, some impoverished regions have successfully marketed local specialty products via live-streaming. Develop community-group buying models, organizing bulk purchase and delivery by neighborhood. This reduces intermediaries and sales costs, while meeting consumer demand for fresh produce. Farmers and enterprises can align production and delivery with community orders, improving planning and precision. Promote “order farming” through digital platforms connecting farmers and enterprises. Enterprises place orders based on market demand, and farmers produce accordingly.

Order farming secures sales channels and lowers farmers' market risks, while ensuring stable raw-material supply for enterprises. For instance, large food processors sign order contracts with farmers to guarantee quality and quantity of inputs.

3.3.4 Evaluation of cost reduction and efficiency improvement

Establish a cost-accounting system to detail distribution costs before and after digital optimization, including logistics, warehousing, and sales costs, analyzing the impact of digital technologies on each[12]. For example, compare transport costs before and after to assess the effectiveness of intelligent transport equipment and routing systems; compare warehousing costs to evaluate benefits of smart warehousing systems. Assess overall benefits by examining increases in sales revenue and cost reductions. For instance, analyze revenue growth from e-commerce and live-streaming, and cost savings from supply-chain coordination and improved logistics efficiency, to calculate net benefit of digital optimization. Set efficiency indicators—such as inventory turnover rate, order-processing time, and transport time—to evaluate distribution efficiency before and after optimization. By comparing these metrics, measure how digital technologies enhance distribution performance; for example, calculate warehouse turnover to assess inventory management improvements, and measure order-processing time to gauge the information-sharing platform's impact on order speed. Collect user feedback to understand satisfaction and suggestions from farmers, enterprises, and consumers regarding digital optimization. Through feedback, identify issues and shortcomings in the process and make timely improvements. For example, use surveys to gauge consumer satisfaction with digitally expanded sales channels and evaluations of product quality and delivery service.

3.4 Digital Innovation in the Sales Link

3.4.1 E-commerce platforms: expanding sales channels and market coverage

In agricultural sales, e-commerce platforms divide into comprehensive platforms and vertical agri-product platforms. Comprehensive platforms like Taobao and JD.com have large user bases and rich traffic, offering wide exposure for products. For example, Taobao's massive user community spans regions and consumer tiers; after listing, sellers can reach hundreds of millions of potential buyers. Vertical platforms such as Benlai Life focus on agri-products, with users more attentive and willing to purchase, facilitating targeted promotion. Traditional sales rely on offline markets and wholesalers, limiting reach to local or nearby areas. E-commerce overcomes geographic barriers, enabling products to reach national and global consumers. For instance, Gannan navel oranges sell not only in major domestic cities but also overseas via e-commerce. Platforms open new sales avenues and reduce intermediaries, allowing farmers to sell directly to consumers and increase profits. On these platforms, products can be showcased with high-quality images, detailed descriptions, and user reviews to highlight unique features and build brands. Specialty items like Wuchang rice and Yantai apples have raised brand awareness and reputation through e-commerce, enabling consumers to choose trusted products and fostering brand loyalty.

3.4.2 Precision marketing: achieving efficient matching between products and consumers

Precision marketing, based on big-data analytics, deeply understands consumer needs, preferences, and behaviors. By collecting users' browsing history, purchase records, and search keywords on e-commerce platforms, and applying advanced analytics, platforms can accurately target products. For example, for consumers who prefer organic vegetables, the platform can push relevant promotions to enhance targeting and effectiveness. Based on targeting results, sellers can launch personalized campaigns—offering first-order discounts to new users and exclusive perks to returning customers. Additionally, use social media for interactive marketing by sharing engaging stories, images, and videos to attract attention and participation, strengthening emotional connections between consumers and products. Precision marketing also involves effective customer-relationship management. By building customer databases and recording purchase information and feedback, sellers maintain long-term communication. Promptly responding to inquiries and complaints improves satisfaction and loyalty. For example, regularly sending care tips or new-product recommendations enhances consumer knowledge and goodwill.

3.4.3 Live streaming: visual demonstration and real-time interaction

In recent years, live streaming has become a new hotspot for agri-product sales. Hosts demonstrate features, growing environments, and usage methods in real time, offering consumers an intuitive understanding. In fruit streams, hosts taste fruits on camera to show taste and freshness, boosting purchase desire. During streams, viewers interact via comments and bullet screens, asking questions and stating needs; hosts answer professionally, enhancing engagement and trust. Streams may include time-limited offers or giveaways to stimulate purchases and drive rapid sales.

3.4.4 Digital supply-chain management: ensuring sales stability

Logistics is a critical link in agricultural sales; digital management improves efficiency and service quality. With logistics information systems, sellers can track transport status in real time, ensuring timely and fresh delivery. For perishable items like seafood and meat, cold-chain logistics provides full-process low-temperature transport to maintain quality. Using digital technologies, sellers achieve precise inventory management. By analyzing and forecasting sales data, they arrange stock levels to avoid overstock or shortages. Inventory-management systems monitor levels in real time and issue replenishment alerts when below safety thresholds, ensuring continuity of sales.

3.4.5 Construction of a digital credit system: enhancing consumer trust

In agricultural sales, building a digital credit system is vital. E-commerce platforms can establish credit-rating mechanisms for sellers and farmers based on consumer evaluations and feedback. Introduce third-party certification for quality and safety—such as green-food and organic certifications—to provide reliable references and boost consumer confidence. Blockchain's decentralization, immutability, and traceability suit credit-system construction: record production, processing, and circulation information on the chain; consumers scan QR codes to view a product's full lifecycle, ensuring quality and safety and further enhancing trust[13].

4 MECHANISMS BY WHICH DIGITAL EMPOWERMENT DRIVES A NEW QUALITY LEAP IN AGRICULTURAL PRODUCTIVITY

4.1 Technology-Innovation-Driven Mechanism

4.1.1 Innovative applications of precision-agriculture technologies

Precision agriculture exemplifies the innovative use of digital technologies in farming by integrating GPS, GIS, remote-sensing (RS), IoT, and other systems to achieve precise management across the production process, thereby markedly enhancing productivity. In sowing, GPS enables tractors and planters to follow preset row and plant-spacing patterns, avoiding uneven seed distribution typical of traditional methods and improving both seed utilization and emergence rates. For instance, in large-scale wheat cultivation, precision sowing yields a more uniform seedling density per square meter, laying a solid foundation for subsequent growth. Coupled with GIS, fields can be zoned according to soil fertility and topography[14], allowing seeds and fertilizers to be applied exactly where needed, tailoring management to local conditions. In fertilization and irrigation, sensor networks play a vital role: soil-moisture and nutrient sensors relay real-time data to intelligent decision systems, which calculate and control the precise volume of water and fertilizer required for each growth stage. This not only boosts resource-use efficiency and cuts waste and pollution, but also meets crops' varying needs as they develop, raising yields and quality. In livestock and poultry farming, digital tools likewise enable precision management: environmental sensors (temperature, humidity, ammonia) continuously monitor barn conditions, triggering alerts and automatic adjustments to ventilation and climate controls whenever parameters stray from optimal ranges. Image-recognition and electronic-tag systems allow individual animals to be tracked and growth metrics—weight, length, feed intake—monitored, so tailored feeding regimes can be applied. For example, in pig farms, smart feeders dispense feed by weight and growth stage, maximizing conversion rates and cutting costs. Real-time health monitoring also detects disease risks early, facilitating prompt prevention and ensuring animal welfare.

4.1.2 Integration of big data and artificial intelligence

The fusion of big data and AI offers intelligent decision support across all farming stages, thus boosting productivity. Agricultural big data encompass meteorological, soil, crop-growth, and market-price information. Sensors, satellites, and drones collect these data continuously and feed them into centralized platforms. Meteorological agencies' satellite and ground-station feeds yield precise weather forecasts to help farmers prepare for extreme events. Soil monitors inform amendment and fertilization plans. Field cameras and sensors track crop growth in real time, guiding management. AI algorithms analyze these vast datasets to uncover patterns and trends: machine-learning models predict growth and yield based on growth data; historical weather and pest-outbreak data feed early-warning systems that forecast pest and disease likelihood and timing, advising farmers on preventive measures. On the market side, AI analyzes price-history trends and current supply–demand dynamics—plus policy shifts—to forecast future price movements, enabling farmers to plan production and marketing strategies that enhance competitiveness.

4.1.3 Blockchain technology ensuring supply-chain efficiency

Blockchain's decentralization, immutability, and traceability underpin efficient supply chains, indirectly elevating productivity. During production, each stage of planting, breeding, processing, transport, and sale is recorded in a tamper-proof chain. Consumers can scan a QR code to view origin, cultivation methods, input usage, harvest time, and logistics details, achieving full traceability. This transparency builds consumer trust and stimulates sales, compelling producers to uphold rigorous quality controls. Blockchain also innovates supply-chain finance. Traditionally, information asymmetry and credit risk make loans scarce for farmers and agri-businesses. On a blockchain platform, stakeholders—farmers, firms, distributors, financiers—share transparent data, enabling lenders to assess real creditworthiness. For example, such platforms can offer order- or warehouse-receipt financing, alleviating farmers' funding shortages and fostering production. Smart contracts automate processes—triggering payments, scheduling logistics, and more when predefined conditions are met—streamlining transactions and slashing costs. For instance, upon a shipment's warehouse arrival, a smart contract can instantly release payment to the producer, bypassing manual settlement delays.

4.1.4 Synergistic innovation of biotechnology and digitalization

The convergence of biotechnology and digital tools opens new avenues for productivity gains. Gene-editing technologies (e.g., CRISPR/Cas9) offer precise, efficient trait improvements; paired with digital systems, they allow exact control and intelligent management of breeding data. By building gene databases and breeding-information platforms, researchers can analyze large genomic datasets to identify yield, quality, and stress-resistance genes, then edit them to develop superior varieties. Digital breeding systems log parental lines, cross combinations, and field performance, supplying data-driven guidance that accelerates breeding cycles and raises efficiency. Biosensors—capable of detecting biomolecules or physiological signals—integrated with digital networks provide real-time monitoring of the agricultural bio-environment. For example, sensors can detect soil microbial communities or pest/disease markers in crop tissues and relay that to decision systems, which then adjust interventions—such as targeted biocontrol agents or fertilization plans. This tight integration enhances precision and sensitivity in agricultural management, advancing fine-tuned control and raising productivity.

4.2 Data-Driven Decision-Making Mechanism

In traditional agricultural decision-making, reliance on experience and intuition can suffice for routine situations but falls short under complex and volatile market and natural conditions, limiting scientific accuracy. The advent of big-data analytics offers a fresh perspective and methodology. By integrating massive agricultural datasets from multiple channels—meteorological, soil, market-price, and produce-sales data—deep mining can reveal hidden patterns and trends, providing scientific basis for decisions in production, sales, and management.

Analyzing meteorological big data allows farmers to anticipate upcoming weather changes and plan planting schedules and crop selection accordingly. For example, if long-term data indicate a region will face low rainfall and high temperatures during a certain period, farmers can choose drought- and heat-tolerant varieties to improve survival rates and yields. Soil big-data analysis helps farmers understand fertility and pH levels to enable precise fertilization and irrigation. By analyzing soil-sample data to determine nutrient content and using soil-moisture sensors combined with weather data, smart irrigation systems can ensure crops receive appropriate water at each growth stage, minimizing waste and pollution.

Big-data analytics also plays a vital role in pest and disease control. By collecting and analyzing historical outbreak data, weather records, and crop-growth information, predictive models can forecast the timing, location, and severity of outbreaks, guiding preemptive measures. For instance, combining years of wheat-rust incidence data with current weather and growth conditions can predict likely rust outbreaks, allowing farmers to prepare control agents and equipment for early intervention, reducing damage and pesticide costs.

Sales-data integration from e-commerce platforms and wholesale markets enables analysis of consumer behavior and demand trends. Mining these data reveals regional and seasonal preferences, guiding adjustments to planting structures. For example, if summer e-commerce data show high demand for watermelon and grapes—especially organic varieties—enterprises can expand organic watermelon and grape cultivation to meet demand, boosting prices and competitiveness.

Because agricultural prices fluctuate with supply-demand, seasonality, and policy, big-data analytics can model and forecast price trends by collecting domestic and international price data and related factors. Producers can then time sales: delaying if prices are expected to rise for higher profits, or accelerating sales to avoid forecasted price drops.

For large farms, efficient resource management—land, labor, equipment—is key to raising efficiency and cutting costs. Sensors and monitoring devices collect data on land use, equipment status, and labor productivity. Analyzing these data uncovers issues and optimization opportunities: identifying high failure rates in machinery requiring maintenance, or reallocating labor tasks and schedules to improve efficiency.

Big-data analytics also enhances supply-chain management by integrating data across production, processing, transport, and sales for end-to-end monitoring and optimization. For instance, analyzing logistics data optimizes transport routes and delivery plans, reducing costs and transit times; real-time monitoring of each link helps detect and resolve issues—inventory backlog or shortages—ensuring stable supply and quality.

Data accuracy and reliability depend on high-quality data. A robust system for data collection, storage, and management is essential: maintaining and calibrating collection devices for accuracy and timeliness, and cleaning and preprocessing to remove noise and errors. Big-data analysis demands multidisciplinary expertise—statistics, computer science, agricultural science—so training is vital. Universities and vocational schools should offer relevant curricula to cultivate talent versed in both agriculture and analytics, while enterprises and research institutes can upskill staff through training and recruitment. In the big-data era, data security and privacy are critical[15]. Agricultural data include sensitive personal and business information, so strong protections—secure storage and transmission, adherence to laws and regulations—must prevent leaks and misuse, safeguarding farmers' and enterprises' rights. By applying big-data analytics in agricultural decision-making, the value of data is fully realized, enhancing the scientific rigor and accuracy of decisions and driving a new quality leap in productivity.

4.3 Industry-Chain Collaboration Mechanism

Information silos across traditional agricultural value chains hinder collaboration. Farmers often lack accurate market-demand data, causing mismatches between supply and demand, leading to unsold produce or price swings. Processors cannot track raw-material supply quality and quantity in real time, disrupting production planning and quality. Distribution suffers from opaque logistics and chaotic inventory management. Digital technologies address these issues effectively.

IoT and sensors at production bases collect real-time soil-moisture, temperature, light, and crop-growth data, uploading them to cloud platforms. Farmers and enterprises can view this data via mobile or desktop to adjust strategies. Big-data analytics forecasts market demand, feeding predictions back to producers to guide planting and breeding.Building an agri-value-chain information-sharing platform is key to seamless data flow. It integrates production, processing, and distribution data—varieties, yields, quality, prices, and logistics status. Stakeholders publish and retrieve information in real time: processors post raw-material needs, farmers adapt cultivation accordingly; logistics providers access transport requirements and locations to optimize routes and schedules. The platform also records transactions and credit ratings, fostering trust and efficiency.

Digital technologies have propelled precision agriculture, enabling fine management. In cropping, GIS, GPS, and remote sensing deliver precise soil-fertility analysis and growth monitoring, allowing targeted fertilization, irrigation, and pest control. In livestock, smart sensors regulate environments and enable precision feeding and disease alerts. These precise data support upstream and downstream coordination: processors use quality and quantity data for accurate production planning; logistics use reliable supply info for efficient transport and storage.Enterprise resource-planning (ERP) and supply-chain-management (SCM) systems integrate production, procurement, inventory, and sales for automated workflows and real-time data exchange. In processing plants, ERP monitors raw-material and finished-goods inventories and production progress, auto-adjusting production and procurement. SCM links suppliers and distributors for synchronized operations, reducing waste and delays and accelerating responsiveness.In logistics, IoT, big data, and AI create “smart logistics.” Vehicle sensors and GPS track cargo location, temperature, and humidity, feeding a logistics platform that optimizes routes and ensures safety. Smart logistics coordinates with processing and sales: sharing production plans and orders to time shipments, enabling seamless chain integration.E-commerce platforms now play a pivotal role, breaking geographic limits and expanding reach. They also provide market feedback via data analytics. To synchronize online and offline channels, integrated sales models are needed: producers open flagship stores online and operate physical outlets for experience-based marketing and after-sales, while offline handles delivery and pick-up, and online drives promotion and traffic, boosting efficiency and satisfaction[16].

Profit distribution in traditional chains is often inequitable, with farmers marginalized. Digital tools support fair distribution by quantifying inputs, outputs, and contributions via big data and blockchain. Blockchain records the entire production-to-sale process—inputs, quality tests, logistics—ensuring tamper-proof data. Contributions are assessed accurately and profits allocated proportionally, incentivizing collaboration and stabilizing the chain.

Industry alliances and cooperatives further collaboration. Digital governance—member management systems, online voting and meetings—enhances management and decision-making. Alliances use digital platforms for training, tech exchange, and marketing, boosting member capacity and competitiveness. Digital governance strengthens cohesion and drives coordinated chain development.

4.4 Market-Response Mechanism

Under traditional models, farmers have limited access to market-demand information and rely on experience, resulting in mismatches and volatility. Digital technologies enable precise market insight. Big-data analytics aggregates vast data from e-commerce, social media, and offline retail to reveal consumer preferences, buying habits, and regional differences. For example, platforms record product categories, brands, specs, and price ranges; analytics predict seasonal and regional demand trends. Farmers and enterprises adjust planting and breeding plans to match demand.IoT in production, transport, and sales also gathers real-time market data. Sensors in storage monitor inventory and quality; when thresholds are reached, the system triggers restocking or promotions to guide strategy.Digital empowerment makes production flexible and controllable, swiftly adapting to market shifts. Smart equipment—automated irrigation adjusting to soil moisture and weather data, and precision fertilization aligning with crop stage—ensures efficient, targeted operations. Adjusting smart equipment parameters accelerates growth and boosts yields when demand surges.Digital management platforms integrate production, sales, and logistics data for real-time visibility into progress, costs, and demand. Managers use cost analyses and market forecasts to decide on harvest timing, sales channels, and pricing in response to price fluctuations.Digital technologies also foster coordinated chain responses: a digital-supply-chain platform lets producers, processors, and logistics share information. When demand changes, each link adapts orders, production, and delivery schedules for timely market supply.Digital empowerment opens new marketing and service avenues, enhancing competitiveness. Online channels—e-commerce sites and social-media accounts—support direct promotion and sales. Live-streaming and short-video marketing attract consumers by showcasing cultivation, environment, and quality. Digital marketing enables precision targeting, pushing personalized product info and promotions.On the service side, CRM systems record purchase histories and feedback, enabling personalized care: automated post-purchase guides and follow-ups resolve issues swiftly. Big-data analytics assesses satisfaction, driving continuous improvement. Blockchain-based traceability records the full lifecycle—planting, harvesting, inputs, processing, and sales—so consumers scan QR codes to verify origin and safety, boosting confidence[17].

Faced with natural and market risks, digital tools enhance risk management. Price-monitoring platforms collect domestic and international price data, and predictive models issue alerts on abnormal swings, prompting farmers to adjust strategies—seeking new channels or value-adding processes to mitigate losses[18].

Supply-demand analytics via IoT and big data track production progress, inventory, and market demand in real time, forecasting shifts so enterprises can optimize production and stock to avoid oversupply or missed opportunities.Digitalization also supports agricultural insurance: big-data platforms aggregate production history, weather, and disaster data to model risk for product design and pricing. IoT and remote sensing monitor crop conditions and detect losses early, improving claim efficiency and accuracy.In summary, digital empowerment—through precise demand capture, agile production adjustment, optimized marketing and service, and bolstered risk response—strengthens market responsiveness and competitiveness, driving a new quality leap in agricultural productivity[19].

5 TYPICAL CASE STUDIES

Case Study 1: A smart farm in China’s eastern coastal region spans about 5,000 mu and focuses on vegetable and fruit cultivation and sales. Beginning digital transformation in 2020, it introduced advanced technologies and management systems to boost efficiency, cut costs, and enhance quality. Sensors in fields monitor soil moisture, temperature, and nutrient content in real time. Via a data-analysis platform, the owner applies precise fertilizer and irrigation based on actual conditions, avoiding waste; fertilizer use dropped by 20% and water-use efficiency improved by 30%. Drones equipped with high-resolution and multispectral cameras conduct field inspections and pest monitoring, quickly pinpointing infestation areas; targeted treatments cut pesticide use by 15%. A farm-management software system digitizes production, sales, and inventory, allowing real-time tracking of crop growth, orders, and stock. When inventory reaches set levels, automated prompts trigger promotions, reducing surplus. A traceability system lets consumers scan QR codes to view the full cultivation, input, harvest, and logistics history, enhancing trust and raising market competitiveness; selling prices rose 10–15%. The farm invests in staff training through workshops and seminars and collaborates with local agricultural institutes for expert guidance, securing technical support and talent. However, initial hardware and software investments reached ￥5 million, imposing financial pressure on a mid-sized farm. Data security measures remain incomplete, risking leaks that could harm business and consumer trust. Some older employees struggle with new systems, hampering adoption and efficiency gains.

Case Study 2: An agri-product e-commerce platform launched in 2018 builds a seamless transaction environment for producers and consumers. It digitized the supply chain end to end, creating traceability from origin to buyer. Partnering with production bases, it integrates planting, harvesting, processing, and transport data on its app for consumer queries, raising quality safety and trust. Big-data analysis forecasts demand and prices, guiding producers on planting structures; order data optimizes logistics for rapid, cost-effective delivery. Focusing on branding, the platform highlights regional specialties with attractive packaging and stories—e.g., a “Local Specialty Fruits” line—drawing consumer attention. Diverse marketing—including social media and live-streaming with influencers—boosts sales; one livestream generated ￥1 million in revenue. To address financing challenges, the platform collaborates with financial institutions to offer supply-chain finance: producers leverage order and credit data for low-interest loans for inputs. Challenges include low standardization of fragmented smallholder output, requiring time-consuming sorting and increasing costs, and uneven quality affecting consumer experience and brand. Perishability and inadequate cold-chain infrastructure cause high transit losses despite mitigation efforts. Intensifying competition demands continuous investment in R&D, branding, and marketing, raising operational costs and risks.

6 CONCLUSION

This study systematically demonstrates the transformative empowerment of the entire agricultural value chain by digital technologies. In the production link, the application of the Internet of Things, drones, and intelligent equipment has achieved precise irrigation, pest and disease control, and enhanced mechanization ; in the processing link, intelligent management and control have raised product standardization levels and driven innovation in high–value-added products; in the distribution link, reliance on e-commerce and digital cold-chain logistics has markedly reduced spoilage rates and transportation costs; and in the sales link, big-data–driven precision marketing and consumer interaction have optimized supply and demand matching. Together, these transformations propel a new-quality leap in agricultural productivity: efficiency gains and cost reductions permeate the entire chain, product quality and added value are significantly enhanced, industry-integration innovations give rise to smart-agriculture business models, and risk-resilience is strengthened through data-driven decision-making. To accelerate agricultural digital transformation, it is necessary to establish a policy framework covering infrastructure (rural networks, big-data platforms), a talent pipeline (skills training and high-end talent attraction), financial support (special funds and financial services), standards systems (technical specifications and data security), and industry collaboration. Future research could deepen evaluations of the long-term mechanisms of digital-technology applications and explore differentiated empowerment pathways for smallholders, thereby fully unleashing the potential for high-quality agricultural development.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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