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Analysis of the driving path of e-commerce to high-quality agricultural development in China: empirical evidence from mediating effect models

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Purpose: This study investigates the impact of e-commerce on high-quality agricultural development (HQAD) in China. As the agricultural sector transitions towards higher quality production in the digital era, understanding the influence pathways and mechanisms of e-commerce becomes crucial. We aim to quantify this influence through a hierarchical approach.

Methods: Utilizing provincial panel data from 2000 to 2021, we construct a comprehensive HQAD evaluation system using the entropy method. Parallel mediating effect models are employed to empirically assess the multi-level effects of e-commerce on HQAD.

Results: Benchmark regression analyzes reveal a significant positive effect of e-commerce on HQAD, indicating its role as a key driver in China's agricultural advancement. Mechanism tests identify several intermediary pathways through which e-commerce indirectly promotes HQAD, including market expansion, agricultural value chain optimization, enhanced social services, and improved infrastructure. Notably, market expansion and value chain optimization demonstrate the most substantial mediation effects, accounting for 43.27 and 14.18% of the total effect, respectively.

Discussion: This research contributes to the literature by establishing a comprehensive HQAD evaluation framework, providing a theoretical foundation for future studies. By incorporating circulation factors into the production system, we elucidate the complex influence mechanisms of e-commerce on agricultural production, addressing a significant research gap. Furthermore, we propose a novel "demand-driven supply optimization" paradigm, offering valuable insights for policy formulation aimed at fostering HQAD in China.

KEYWORDS

e-commerce, high-quality agricultural development, mediation effect, agricultural economic growth, green agricultural development

1 Introduction

China, a developing nation with a population of 1.4 billion, heavily relies on its agricultural sector to ensure food safety and ecological stability. The agricultural sector, a cornerstone of the national economy, has undergone significant transformations driven by industrialization. Grain production has increased dramatically from 304.77 million tons in 1978 to 686.53 million tons in 2022, successfully meeting the nutritional needs of the population. However, this progress has been accompanied by environmental degradation, food safety concerns, climate change impacts, and biological invasions. As living standards improve, consumer preferences are shifting towards healthier and safer food products. Consequently, enhancing agricultural quality has become crucial for ensuring global food security, promoting human well-being, and supporting robust economic development (Garibaldi et al., 2011).

The concept of high-quality development, introduced by the Chinese government in October 2017, has emerged as a new imperative for the agricultural sector (Wang D. et al., 2022; Wang G. et al., 2022). While HQAD has garnered global attention, it remains in its nascent stages. Traditional approaches to promoting HQAD have focused on input factors such as land, labor, capital, fertilizer, and irrigation, as well as their allocation efficiency (Chi et al., 2022). However, in the absence of technological advancements, the law of diminishing returns limits the sustainability of this approach. Recent scholarly attention has shifted towards digital and biotechnologies (Tang and Chen, 2022), yet these predominantly address production efficiency through altered input combinations, often neglecting the crucial aspect of market circulation – a significant obstacle to HQAD, given the perishable nature of most agricultural products (Ashokkumar et al., 2019).

The emergence of "Internet +" as a new economic paradigm since the 1990s has given rise to e-commerce, an advanced business model leveraging computer networks. E-commerce, underpinned by internet infrastructure and information technology, offers advantages such as high efficiency and strong profitability (Gai, 2023). Its integration with agriculture encompasses various aspects, including industrial layout, value chain development, logistics optimization, product sales and service, and brand management. This convergence applies modern information technology and management methods to agricultural product sales, revolutionizing both production methods (Tang, 2022) and consumption patterns. The rise of online retail, booking, purchasing, and payment reflects a shift towards a "customer-centric" approach (Zhang and Berghäll, 2021), transforming the traditional supply-driven agricultural development model into a demand-driven paradigm (Nosratabadi et al., 2020). At the micro level, agricultural producers' organizations are deepening vertical cooperation within the industry through increased consolidation to access larger markets and higher economic profits. The application of internet-based remote planning and monitoring facilitates the optimization of procedures and decision-making, ultimately improving agricultural product quality (Nosratabadi et al., 2020). At the macro level, the reduction in fertilizer use, improvements in technical efficiency, increased farmland utilization, and enhanced farmer welfare (Twumasi et al., 2021; Zhang and Berghäll, 2021; Zhu et al., 2021) reflect the intrinsic demands of high-quality agriculture. The deep integration of e-commerce and agriculture provides new avenues for agricultural transformation and upgrading.

This study investigates the driving pathways through which e-commerce contributes to HQAD. The paper is structured as follows: Section 2 presents a theoretical discussion on the action mechanism, elucidating the internal processes by which e-commerce promotes HQAD. Section 3 employs the entropy method to establish an evaluation system for HQAD and quantifies China's development index based on provincial data. Section 4 decomposes and measures the driving impact of e-commerce through an empirical analysis of mediating effects. Finally, Section 5 offers conclusions and policy recommendations.

2 Literature review and research hypostudy

2.1 Literature review

The evolution of modern agriculture has witnessed a paradigm shift from "efficiency pursuit" to "green production" and, more recently, to "high-quality development" (Wang D. et al., 2022; Wang Z. et al., 2022). Contemporary scholarly discourse on HQAD primarily focuses on four key aspects: conceptual definition, characteristic identification, measurement methodologies, and influencing factors.

2.1.1 Definition of the connotation of HQAD

HQAD emerges as a product of China's economic development trajectory, signifying a transition from a quantitative "having or not" paradigm to a qualitative "good or bad" evaluation of agricultural production. As a nascent concept, recent scholarly endeavors have explored its multifaceted connotations, broadly categorized into three perspectives. (1) Development concept-based approach. In contrast to traditional agriculture, HQAD is guided by principles of "innovation, coordination, green, openness, and sharing" (Cui et al., 2022), reflecting the extent to which these five concepts are operationalized in the production process. (2) Production efficiency perspective. The crux of HQAD lies in the adoption of resource-efficient technologies, optimal allocation of production factors, and enhancement of total factor productivity, epitomizing an intensive mode of production (Baráth et al., 2020). This approach emphasizes not only the scale and speed of agricultural product supply but also quality and efficiency (Tang and Chen, 2022). (3) Agricultural function-based view. The evolutionary trajectory of agriculture has seen an expansion from its primary food provision function to encompassing industrial raw material supply, labor provision, and more recently, services such as leisure tourism, cultural preservation and innovation, and environmental stewardship (Pang et al., 2016). Consequently, HQAD emphasizes the synergy between economic functions and environmental protection, as well as human social development (Chi et al., 2022). HQAD thus emerges as a multidimensional construct necessitating a comprehensive examination of its conceptual, production, and social systems. Current scholarly efforts, while valuable, remain fragmented, lacking a cohesive theoretical framework.

2.1.2 Research on the measurement of HQAD

While the HQAD concept originated in Chinese academia, parallel global discourses on sustainable and smart agriculture reflect similar aspirations. Measurement methodologies have evolved from singular indicators to comprehensive evaluation systems (Bao et al., 2021), primarily focusing on: (1) Agricultural production efficiency. Scholars employing Data Envelopment Analysis (DEA) have identified that non-agricultural employment negatively impacts agricultural production efficiency (Chang et al., 2022). Conversely, enhanced land tenure rights both directly and indirectly improve efficiency through increased agricultural investment (Zhang and Chen, 2022). (2) Green ecological efficiency. The approach to measuring green ecological efficiency in agriculture has developed along two main streams. The first stream focuses on constructing comprehensive green agriculture evaluation systems. For instance, Bergius et al. (2018) assessed green agriculture development in Tanzania's Southern Agricultural Growth Corridor (SAGCOT) across dimensions such as resource utilization efficiency and ecological stability. Similarly, Yao and Sun (2023) employed indicators including agricultural resource input, total agricultural output value, and carbon emissions to gauge green agriculture development in China. The second stream concentrates on measuring agricultural green total factor productivity. Scholars in this area have employed various methods, including Stochastic Frontier Analysis (SFA) (Orea and Wall, 2017), Data Envelopment Analysis (DEA) (Suzigan et al., 2020), and Undesirable Slacks-Based Measure (SBM) (Guo et al., 2015) to quantify and analyze the agricultural green total factor productivity. (3) Quality evaluation systems. Recent scholarship has reconstructed HQAD evaluation systems based on the five development concepts: green, innovation, opening, coordination, and sharing (Liu et al., 2020; Wang H. et al., 2022). Findings suggest that in China, the green dimension exhibits the most rapid development, followed by innovation and sharing (Cui et al., 2022). Scholars have also developed evaluation systems for green agriculture, high-quality agriculture, and brand agriculture (Lu et al., 2022). Prevalent methodologies include the entropy method (Wang S. et al., 2021; Wang G. et al., 2022; Yang et al., 2023), TOPSIS (Li et al., 2023), and fuzzy analytic hierarchy process. Despite these advancements, research on HQAD measurement remains limited, with significant variations in results due to disparities in indicator selection and calculation methodologies.

2.1.3 Research on the influencing factors of HQAD

HQAD is a complex, multifaceted endeavor influenced by numerous factors. Current scholarly discourse primarily analyzes these influencing factors through the lenses of agricultural industrial agglomeration, technological innovation, and market conditions. (1) Industrial agglomeration. The concentration of agricultural industries has facilitated economies of scale and improved infrastructure utilization (Guo et al., 2020). This agglomeration fosters resource sharing and technology diffusion, attracting key factors such as scientific personnel and green mechanization, thereby enhancing green total factor productivity (GTFP) (Li et al., 2017). However, excessive agglomeration can lead to crowding effects, potentially impeding agricultural development (Yin and Wu, 2021). Xu et al. (2022) employed Moran's I index and the spatial Durbin model (SDM), revealing a U-shaped relationship between the degree of agricultural industrial agglomeration and green development. (2) Technological innovation. Innovation plays a pivotal role in the evolution of traditional agriculture in China. Advancements in cultivation techniques, efficient resource utilization, and pollution mitigation are key drivers of progress (Chandio et al., 2023). HQAD is characterized by digitalization and informatization, propelled by technologies such as robotic systems and smart machines (RSSM), and farm management information systems (Schwering et al., 2022). Precision and smart agriculture represent the primary developmental trajectories. Higgins et al. (2017) posit that the adoption of precision agriculture technologies has reduced production and operational costs while augmenting the value of the agricultural industry chain. In China, a 1% increase in research and development investment correlates with a 1.79% improvement in HQAD levels (Yang et al., 2023). (3) Market conditions. The degree of marketization, encompassing factors such as the business environment and agricultural openness, exerts a long-term positive influence on agricultural sector in China (Wang D. et al., 2022; Wang H. et al., 2022). Enhanced market conditions facilitate the innovative application of new technologies and the modernization of agricultural operations, guiding the optimization of the agricultural industry chain (Soegoto and Faridh, 2020; Molina et al., 2024). Within the market sphere, financial product innovations, such as digital inclusive finance, have provided accessible financial services (Li et al., 2023).

2.1.4 Research on the impact of e-commerce on agriculture

Among the myriad factors influencing agricultural development, scholars have increasingly recognized the significance of e-commerce. The research in this domain can be categorized into the following aspects. (1) Impact on green agricultural development. Studies have focused on whether e-commerce mitigates agricultural pollution. Evidence suggests that e-commerce promotes green agriculture by catalyzing industrial restructuring and facilitating green technology innovation (Han et al., 2023). (2) Influence on consumer behavior. Bai et al. (2024) investigated emerging e-commerce modalities, finding that live-streaming e-commerce significantly enhances consumer purchase intention due to its real-time experiential advantages. However, purchase intention and satisfaction are influenced by multiple factors, including consumer expectations, product quality, brand image, e-commerce platform characteristics, and logistics efficiency (Liu and Kao, 2022). Maintaining consumer satisfaction has emerged as a critical challenge for agricultural product suppliers (Zaghloul et al., 2024). (3) Impact on agricultural product sales efficiency. E-commerce connects global internet platforms, generating powerful resource integration effects and information resource advantages. This integration encompasses previously dispersed supply chain resources and information and communication technology infrastructure (Farid and Riaz, 2023). Additionally, vast amounts of agricultural data are collected and utilized in information dissemination systems (Kinsey and Buhr, 2003). To leverage the positive impact of e-commerce on agriculture, website functionalities and communication strategies should be tailored to different farmer typologies, such as professional operators, online hesitators, offline loyalists, and online enthusiasts, based on their distinct characteristics. While these studies do not directly examine the impact of e-commerce on HQAD, they collectively indicate that e-commerce is an essential factor promoting agricultural modernization from various perspectives.

Extant literature has made substantial contributions to our understanding of agricultural development. Scholars have elucidated various factors influencing agricultural productivity and sustainability (e.g., Guo et al., 2020; Wang Z. et al., 2022). Nevertheless, several limitations persist in the current body of research. First, studies predominantly emphasize supply-side factors, often neglecting demand-side drivers such as e-commerce (Li et al., 2023). Second, there is a dearth of comprehensive frameworks that simultaneously explore multiple pathways of influence, limiting our understanding of the complex interplay between e-commerce and various aspects of agricultural development (Zhang and Berghäll, 2021). Third, existing evaluation systems for HQAD frequently omit the social contribution dimension, resulting in an incomplete assessment of agriculture's multifaceted impact (Chi et al., 2022). These gaps in the literature underscore the necessity for a more holistic approach to studying HQAD, one that incorporates demand-side factors, examines multiple pathways, and encompasses a broader spectrum of evaluation criteria.

This study makes several significant contributions to the existing literature on HQAD. Firstly, unlike previous research focusing on supply-side factors (Guo et al., 2020; Chandio et al., 2023), we identify e-commerce as a key driver from the demand side, offering fresh insights into agricultural advancement mechanisms. Secondly, we propose and empirically test multiple pathways through which e-commerce influences HQAD, including market expansion, agricultural industry chain optimization, social service improvement, and infrastructure supply enhancement. This comprehensive framework provides a more nuanced understanding of e-commerce's role. Lastly, we improve upon existing assessment models by incorporating agricultural social contribution as a new dimension, alongside agricultural quality and efficiency, innovation capability, and green development. This enhanced evaluation system offers a more holistic view of agricultural development's impact.

2.2 Research hypostudy

HQAD represents an innovative approach to sustainable development, with e-commerce serving as a crucial component within the "Internet+" framework. The integration of e-commerce signifies market convergence and a customer-centric paradigm (Schwering et al., 2023), offering substantial benefits in resource integration and information accessibility. By leveraging the "power source," "supply chain," and "guarantee chain," e-commerce facilitates a seamless connection between circulation and production, thereby fostering HQAD. These impact mechanisms are illustrated in Figure 1.

2.2.1 E-commerce, market expansion, and HQAD

HQAD epitomizes the optimization of production methods under market forces, with sustained market demand serving as the "power source." Agricultural producer organizations, as profit-driven entities, aim to maximize economic returns (Pendyala et al., 2022). Their investment decisions and production practices are influenced by market price signals. However, the fragmentation of agricultural product markets across regions disrupts the efficient transmission of price signals, resulting in reduced income. Traditional offline distribution of agricultural products heavily relies on intermediaries, and information asymmetry limits farmers' ability to influence market prices, leading to lower farmgate prices (Ashokkumar et al., 2019). Consequently, intermediaries capture a significant portion of agricultural profits. Compared to non-agricultural sectors, agricultural production is characterized by high risks, labor intensity, and low returns. This economic disparity has led to substantial rural–urban migration and impeded the qualitative improvement of agricultural practices. The critical challenge lies in eliminating information barriers between farmers and broader markets.

Concurrently, the disintermediation effect of e-commerce provides farmers with alternative marketing channels and access to a wider consumer base, thereby enhancing distribution efficiency. Farmers can directly engage with larger markets and increase their share of the final product value (Kumar et al., 2023). Recently, established e-commerce platforms such as Taobao and JD.com have introduced innovative "live+e-commerce" models. The integration of technologies like Virtual Reality (VR) and Augmented Reality (AR) offers consumers an immersive 3D shopping experience that stimulates multiple senses, including visual, auditory, and tactile, thus enhancing consumer engagement (Ricci et al., 2023). These technologies not only excel in product visualization (Chen et al., 2024) but also enable more robust interactions, increased transparency,

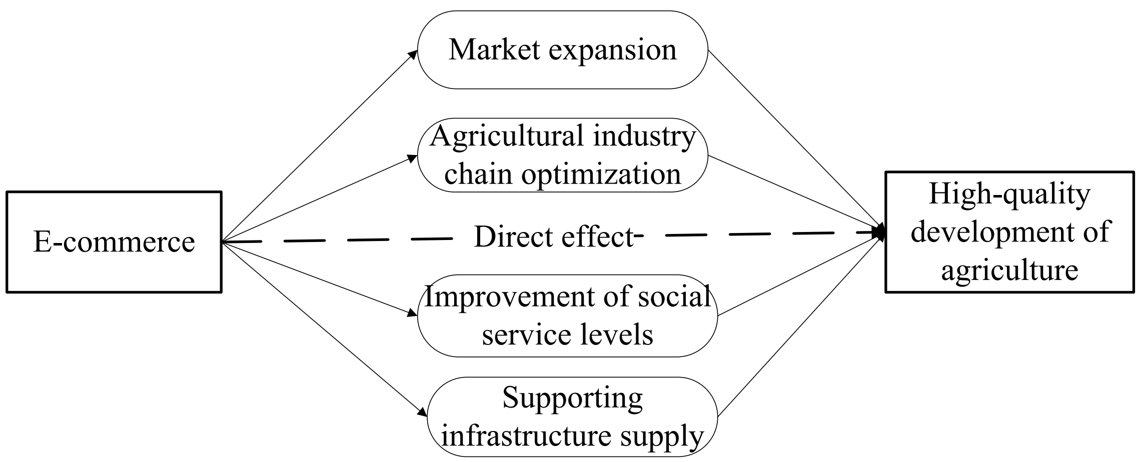

FIGURE 1
The mechanism of e-commerce affecting the HQAD.

higher conversion rates, and stronger customer loyalty. The emergence of new market segments such as contract farming, agritourism, and rural tourism has propelled agriculture from low value-added activities to medium and high-end market tiers. E-commerce model innovations have enhanced information accessibility and logistics efficiency, expanded the market reach of agricultural products, and generated a significant market discovery effect. Simultaneously, e-commerce demonstrates a substantial market integration effect. Agricultural e-commerce platforms like Taobao, JD.com, and Pinduoduo not only extend online markets but also integrate offline markets. Information disclosure, product standardization, logistics, and services in agricultural markets nationwide are increasingly harmonized. In 2021, rural online retail sales in China reached 2.17 trillion yuan, accounting for 14.8% of total agricultural product sales (Feng, 2023), with the market size of live e-commerce surpassing 1.2 trillion yuan by 2022. Based on these observations, we propose the following hypothesis:

> *H1:* E-commerce facilitates market expansion both online and offline, thereby providing a stronger "power source" for HQAD.

2.2.2 E-commerce, agricultural industrial chain and HQAD

Traditional small-scale agriculture is characterized by decentralization and limited scope. In the context of large-scale and high-end agricultural development trends, small-scale production faces challenges such as insufficient scientific and technological expertise and inadequate investment capital (Lin and Wang, 2014). The lag in organizational structure remains a primary barrier to HQAD. The agricultural industry chain comprises various organizational elements, including upstream (agriculture), midstream (agricultural product processing enterprises), and downstream (service industry) sectors. To achieve HQAD, it is crucial to vertically integrate resources across the entire industrial chain and align with advanced organizational modes and management practices. E-commerce, as an innovative technology leveraging the Internet for trade, offers key functionalities in vertical integration and efficient supply chain management. The synergy between e-commerce and agriculture presents promising prospects, attracting leading e-commerce enterprises, network anchors, and social capital. The traditional "farmers + wholesalers + retailers" supply chain model has evolved into a multi-agent chain involving "e-commerce enterprises + production bases + professional cooperatives + social capital." E-commerce platforms facilitate the transformation of agricultural products into standardized logistics systems, establishing various quality control measures such as product standards, supply assurance, organic traceability, and premium brand development. Within the virtual supply chain, order-based and contract-based systems assist farmers in adopting market-oriented mindsets. The vertical integration of the supply chain system shifts the mode of operation from individual independence to cooperative multi-agent approaches.

Customer retention is a critical factor in the development of e-commerce and HQAD. E-commerce enterprises can leverage big data analytics to comprehensively understand consumer demand fluctuations and user feedback. The application of mathematical models enables effective differentiation of user interests, optimizing system recommendations and marketing strategies (Ma and Wang, 2024). Concurrently, agricultural product quality plays a pivotal role in influencing consumers' purchasing decisions and satisfaction levels. Contemporary consumers increasingly demand refined and high-end agricultural products. While common products struggle to find markets, premium and environmentally friendly products are in high demand, highlighting a misalignment in the supply structure of agricultural products (Zhou et al., 2019). E-commerce facilitates the networking of information flow, capital flow, and logistics, emphasizing "wireless connectivity" and "information sharing." The traditional "price-centered" market approach is being supplanted by a new "data-centric" model. Market demands and data signals are driving the need for branding, sustainability, and optimization of agricultural supply chains. Online platforms showcase the entire process of agricultural production and processing, allowing consumers to easily trace product origins through QR code scanning, thereby enhancing user loyalty. By 2021, 24.7% of Chinese agricultural products achieved quality and safety traceability. Data mining studies have demonstrated that the prediction accuracy of attribute analysis tools is 20.36% higher than that of general analysis tools (Yang, 2022). Based on these observations, we propose the following hypothesis:

> *H2:* The vertical synergy effect of e-commerce drives the industrialization of agricultural organizations. Through the mediation of the "industrial chain," e-commerce promotes HQAD.

2.2.3 E-commerce, social service, and HQAD

HQAD relies not only on technological innovation in production but also on the support of various social services, including operational management, financial insurance, information consulting, brand operation, and marketing circulation (Chen et al., 2021). As agricultural technology advances, the level of division of labor and specialization in agriculture deepens, creating opportunities for market-oriented e-commerce operations in the service sector (Zhong et al., 2022). Currently, e-commerce companies are evolving into service platforms, offering farmers modern service "tools" by integrating online and offline agricultural technologies, resources, financial services, and logistics solutions. International examples demonstrate the positive impact of e-commerce on agricultural development. For instance, e-wallet technology has enabled more than 50% of Nigerian farmers to access improved seeds and fertilizers (Adebo, 2014). E-commerce has supported Bangladeshi farmers in enhancing their technologies and modernizing agriculture by facilitating access to funds from credit institutions (Khandker and Koolwal, 2016). In Pakistan, crop yields have seen significant growth following the provision of agricultural consulting and financial services to farmers (Elahi et al., 2018). In China, comprehensive e-commerce providers such as "JD Agricultural Materials" and "Rural Taobao" treat agricultural inputs like seeds, feed, fertilizers, pesticides, and machinery as tradable commodities. They offer farmers online purchasing and machinery operation services, aiding in cost reduction and shortened procurement cycles. Service-oriented agricultural e-commerce providers such as "Nong Yi Sheng" and "Yi Nong Bao" promptly update agricultural technology and product information to offer farmers online consultation and diagnostic services, enhancing their knowledge and production skills (Du et al., 2023).

Vertical agricultural e-commerce platforms like "Feng Shou Xia" assist farmers in acquiring, storing, and transporting agricultural products through offline service stations and social networks, enabling them to effectively market their goods. Since its inception in 2018, "Feng Shou Xia" has served over 100,000 farmers, significantly boosting their income. Based on these observations, we propose the following hypothesis:

> *H3:* E-commerce leads the modernization of agricultural social services. Through the mediation of social services, e-commerce strengthens the soft "security chain" for HQAD.

2.2.4 E-commerce, infrastructure, and HQAD

HQAD requires the implementation of a comprehensive quality control system that prioritizes green, organic, and pollution-free production methods to ensure the cultivation of nutritious, safe, and reliable agricultural products. This agricultural transformation is contingent upon the availability of critical infrastructure, including robust power supply networks, extensive telecommunications coverage, and efficient logistics systems, with a primary focus on modern facilities and advanced technological investments (Usman et al., 2024). Since the early 21st century, the Chinese government has significantly increased investments in rural infrastructure to support the expansion of e-commerce into agrarian regions. A notable initiative is the "E-commerce into Village" project, launched in 2014, which aims to enhance rural e-commerce service points, establish comprehensive logistics networks, develop robust supply chains and regional brands, and improve farmer training programs (Xin, 2021). By 2021, broadband coverage in China's administrative villages had achieved full penetration, with optical fiber and 4G network coverage exceeding 99%. Furthermore, by the end of 2022, 5G network deployment had been completed in county and urban areas. The elimination of infrastructural barriers is crucial in enabling rural regions to establish self-sustaining e-commerce ecosystems (Leong et al., 2016).

Concurrently, vendors on major e-commerce platforms such as Amazon, JD.com, and Suning are evolving beyond their traditional roles as intermediaries. These entities are increasingly establishing self-operated stores, engaging in logistics and warehousing operations, and providing specialized services such as cold chain logistics for agricultural products (Han et al., 2023). This transformation has been conceptualized by scholars like Qin et al. (2021) as the "market-platform" model. According to Tosza (2021), e-commerce can be categorized into rule-setter and infrastructure providers. In the current market landscape, the provision of efficient logistics services has become a critical determinant of e-commerce platforms' competitive advantage. The infrastructural impact of e-commerce advancement extends to agricultural production methods. Modern logistics facilities, coupled with advanced equipment and technologies such as automated production management control systems and integrated water and fertilizer management, are being extensively utilized to facilitate the automation of farming, animal husbandry, and aquaculture practices. This technological integration addresses the "hardware" deficiencies in agricultural transformation and enhancement, fostering sustainable production practices such as ecological farming and circular agriculture (Zheng and Zhou, 2023). Based on these observations, we propose the following hypothesis:

> *H4:* The proliferation of e-commerce has catalyzed increased investment in rural infrastructure by both enterprises and government entities. Through the modernization of logistics and other critical infrastructure, e-commerce provides the hardware for HQAD.

3 Construction of index system and its research methods

3.1 Construction of index system of HQAD

In recent years, HQAD has emerged as a significant focus in academic research, with numerous scholars assessing its developmental level. Baráth et al. (2020) utilized total factor productivity as a proxy variable to evaluate the level of HQAD in Slovenia. Concurrently, Chinese scholars have explored the construction of multidimensional index systems. For instance, Liu et al. (2020) established a comprehensive evaluation framework based on five new development concepts: innovation, coordination, green development, opening up, and sharing. Li et al. (2023) formulated an evaluation index system encompassing aspects such as farmer income, industrial efficiency, technological support, production efficiency, labor quality, and green production. Building upon existing research, this study has developed a comprehensive index system for HQAD, focusing on agricultural quality and efficiency enhancement, agricultural innovation capability, agricultural green development, and agricultural social contribution.

1. Agricultural quality and efficiency enhancement. The HQAD framework necessitates consistent productivity growth while emphasizing qualitative and efficiency improvements. This study incorporates five key indicators to comprehensively assess the enhancement of agricultural quality and efficiency: agricultural labor productivity, agricultural land yield, agricultural economic development, structural composition of the agricultural sector, and agricultural export competitiveness.
2. Agricultural innovation capability. Technological advancement is fundamental to HQAD. The integration of cutting-edge technologies and agricultural mechanization significantly influences production efficiency and product quality. Drawing from extant literature, this study employs indicators such as the degree of agricultural mechanization, agricultural financial allocation, research and development (R&D) investment intensity, proportion of R&D personnel, and shifts in the agricultural industrial structure to evaluate innovation capability.
3. Green agricultural development. HQAD prioritizes sustainable resource utilization, energy efficiency, and environmental stewardship throughout the production process. To gauge the level of green development, this study utilizes key indicators including the effective irrigation coefficient, agricultural fertilizer application intensity, pesticide utilization rate, and agricultural carbon emissions.

4. Agricultural social contribution. The primary objective of agricultural development is to meet societal needs. HQAD emphasizes the social benefits of agriculture and its active contribution to societal progress. Consequently, this study incorporates indicators such as the agricultural labor employment ratio, rural resident income levels, rural residents' Engel coefficient, agricultural GDP contribution rate, and urbanization rate to assess the social impact of the agricultural sector.

3.2 Data sources

This study examines different provinces in China (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2000 to 2021 as case studies. The data utilized primarily came from the China Statistical Yearbook, China Rural Statistical Yearbook, China Financial Statistical Yearbook, China Science and Technology Statistical Yearbook, China Environmental Statistical Yearbook, China Population and Employment Statistical Yearbook, and the statistical yearbook of each province.

3.3 Description of research methods

This study employs the entropy method to evaluate the target layer and each criterion layer by analyzing data index fluctuations. The methodological approach comprises three main stages. First, the extreme value method is applied to normalize the original data and compute the relative weights of individual indices. Second, the entropy, difference coefficient, and weight of each index are calculated to assess the information content and discriminatory power of the indicators. Third, the indices for the four dimensions are computed, and subsequently, a comprehensive development index is derived using an objective linear weighting function. The detailed procedural steps for this analysis are as follows.

(1) Data standardization processing. For positive indicators, the data are standardized using Equation (1) as shown below:

$$x_{ij}^{*} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

For negative indicators, Equation (2) is applied for standardization:

$$x_{ij}^{*} = \frac{maxx_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

where, x_{ij}represents the original data of j indicator of i region, $\min x_{ij}$ is the minimum value of the indicator, $\max x_{ij}$ is the maximum value of the indicator, and $x_{ij}^{*}$is the result after standardization of the indicator x_{ij}.

(2) Normalize the indicators and calculate the proportion of the Jth indicator in the region i, as shown in Equation (3):

$$X_{kij} = \frac{x_{kij}^{*}}{\sum_{i=1}^{n} x_{kij}^{*}} \tag{3}$$

(3) Calculate the information entropy of the index e_j, as indicated by Equation (4):

$$e_j = -\frac{1}{\log_n} \sum_{j=1}^{m} X_{ij} * \log X_{ij} \tag{4}$$

where e_j is the information entropy of the Jth index, n is the number of provinces to be evaluated, $n = 31$.

(4) Calculate the difference coefficient g_j and weight w_j of the Jth index using Equations (5, 6), respectively, as follows:

$$g_j = 1 - e_j \tag{5}$$

$$w_j = \frac{g_j}{\sum_{j=1}^{m} g_j} \tag{6}$$

where g_j is the difference coefficient of the Jth index, and the larger the coefficient, the greater the effect of this index on the object of study, and the more important this economic index.

(5) According to the weights calculated in (4), the standardized indicators in (1) is weighted and summarized to obtain the comprehensive indicator of HQAD.
(6) Repeat steps (1) to (5) by different years. The construction of evaluation system of HQAD index is shown in Table 1.

3.4 Construction of e-commerce development index

The assessment of e-commerce development employs various methodologies, including the e-commerce readiness framework developed by the Asia-Pacific Economic Cooperation (APEC) and the life cycle model proposed by the Organization for Economic Co-operation and Development (OECD). In the Chinese context, the China Internet Research and Development Center (CIRC) has formulated a comprehensive e-commerce index comprising 32 indicators, tailored to the nation's specific circumstances. This study builds upon existing research by synthesizing multiple sources to construct a robust index system. Primary references include the E-commerce Development Index in China published by the Chinese Academy of Social Sciences and the index system released by the CIRC. The selection of indicators was further refined based on the availability of relevant data across various provinces. The index system is presented in Table 2.

4 Empirical measurement of e-commerce driving HQAD in China

4.1 Basic model setting

Drawing upon the aforementioned theoretical framework, this study proposes a basic econometric model to empirically examine the impact of e-commerce on HQAD. The model is specified as follows.

TABLE 1 Construction of evaluation system of HQAD index.

First-class index	Second-class index	Implication	Attribute
Improvement of agricultural quality and efficiency	Agricultural labor productivity	The ratio of the total output value of agriculture, forestry, animal husbandry and fishery to the employed population of agriculture in each region	Positive
	Agricultural land yield	Ratio of total agricultural output value to crop acreage in each region	Positive
	Agricultural economic development status	The total output value of agriculture, forestry, animal husbandry and fishery in each region	Positive
	Agricultural structure	The ratio of total output value of animal husbandry and fishery to total output value of agriculture, forestry and animal husbandry and fishery in each region	Negative
	Agricultural export competitiveness	TC index of agricultural products	Positive
Agricultural social contribution	Employment ratio of agricultural labor force	The ratio of employed population in agriculture, forestry, animal husbandry and fishery to employed population in agriculture in each region	Positive
	Income level of rural residents	Disposable income levels of rural residents in each region	Positive
	Engel coefficient of rural residents	The ratio of food and tobacco expenditure of rural residents to total consumption expenditure in each region	Negative
	Contribution rate of agricultural GDP	The ratio of total output value of agriculture, forestry, animal husbandry and fishery to GDP in each region	Positive
	Urbanization rate	The proportion of rural population in urban population in each region	Positive
Agricultural green development	Effective irrigation coefficient	The proportion of effective irrigated area in cultivated land area of each region	Positive
	Agricultural fertilization intensity	Fertilization intensity in cultivated land area of each region	Negative
	Pesticide application intensity	Pesticide application intensity in cultivated land area of each region	Negative
	Agricultural carbon emission	Agricultural electricity consumption in each region	Negative
Agricultural innovation ability	Level of agricultural mechanization	Total power of agricultural mechanization in each region	Positive
	Agricultural fiscal expenditure	Agricultural fiscal expenditures in each region	Positive
	R&D investment intensity	Ratio of R&D expenditure to GDP in each region	Positive
	Proportion of R&D personnel	The ratio of R&D personnel to total employed personnel in each region	Positive
	Industrial structure adjustment of agriculture	1- (Total agricultural output value/Total output value of agriculture, forestry, animal husbandry and fishery)	Positive

The data came from China Statistical Yearbook, China Rural Statistical Yearbook and Customs Import and export database. For the values missed, linear interpolation method is used to complete them.

$$\text{quality}_{it} = \alpha_0 + \alpha_1 \text{ec}_{it} + \alpha_j \sum_{i=1}^{n} X_{jit} + \delta_i + \mu_t + \varepsilon_{it} \tag{7}$$

where quality_{it} represents the HQAD index provinces i in the year t; ec_{it} stands for the e-commerce development index; X stands for the other possible control variable and ε_{it} is the error perturbation term. If α_1 is significantly positive, that means the e-commerce has boosted HQAD.

4.2 Variable selection

To enhance the robustness of our analysis on the impact of e-commerce, this study incorporates several potential confounding factors as control variables. (1) Crop disaster rate, measured as the ratio of disaster-affected crop area to total planted area in each region. (2) Foreign direct investment (FDI) level, calculated as the ratio of FDI (converted to Chinese yuan using the annual average exchange rate) to GDP. (3) Financial development level, represented by the ratio of outstanding financial credits to total regional output. (4) Macroeconomic environment, indicated by the proportion of secondary and tertiary industry output to total regional output. (5) Whether to cancel agricultural tax or not. Considering the policy factor that China completely abolished agricultural tax on January 1, 2006, a dummy variable is set for the cancellation of agricultural tax, with a value of 0 before 2006 and 1 after 2006. (6) The density of rural roads. Following Tian and Xiong (2023), the density of rural roads is calculated as (regional highway mileage – regional first-class highway mileage – regional second-class highway mileage + out-of-region highway mileage) / (regional area – regional construction area). The descriptive analysis of the relevant variables is presented in Table 3.

4.3 Benchmark regression and result analysis

The benchmark regression analysis, aimed at evaluating the impact of e-commerce on HQAD, yielded a statistically significant coefficient of 0.147. This finding underscores the substantial influence of e-commerce on agricultural sector in China. The proliferation of e-commerce platforms in recent years has revolutionized the distribution channels for agricultural products in China, offering a more efficient and accessible marketplace. By streamlining processes

TABLE 2 Construction of index system of e-commerce development level.

First-class index	Second-class index	Implication	Attribute
E-commerce readiness degree	Information fixed asset investment	Investment in fixed assets in information transmission, software and information technology services by regions	Positive
	Internet penetration rate	The proportion of broadband access users in the total population at the end of the year by regions	Positive
	Telephone penetration rate	The proportion of telephone users in the total population at the end of the year by regions	Positive
E-commerce use degree	E-commerce transaction size	E-commerce sales by regions	Positive
	Express business volume	Number of express business by regions	Positive
	E-commerce employees	Number of employees in the e-commerce industry by regions	Positive
	Telecommunication business volume	Total telecommunications services by regions	Positive
E-commerce impact degree	The contribution of e-commerce to GDP	The ratio of e-commerce trading volume to GDP by regions	Positive
	The proportion of B2B trading volume in consumption	The ratio of e-commerce trading volume to total consumption by regions	Positive
	Revenue from transportation, warehousing and postal services	Total salaries of employees in the transportation, warehousing and postal industries by regions	Positive

The data came from China E-commerce Report and China Statistical Yearbook released by the Ministry of Commerce. For the values missed, linear interpolation method is used to complete them.

across the agricultural supply chain, including procurement, storage, and delivery, e-commerce has effectively mitigated costs and enhanced operational efficiency. These improvements have, in turn, contributed significantly to the advancement of China's HQAD. Table 4 presents a comprehensive breakdown of our regression results, providing further insights into the magnitude and nature of this relationship.

4.3.1 Robustness test

To further validate the robustness of our findings regarding the impact of e-commerce, we employed several alternative methodologies, with results presented in Table 5. Firstly, we conducted new our explanatory and dependent variables, utilizing principal component analysis to reconstruct both the e-commerce and HQAD indices for regression analysis. As evidenced in column (1) of Table 5, the newly constructed e-commerce development index continues to exhibit a significant positive effect on the revised HQAD index. Secondly, we incorporated a joint fixed effect model, accounting for both control area and year, which reaffirmed the conclusions drawn from our baseline regression. Lastly, to mitigate the potential influence of outliers, we applied a winsorization technique at the 1% level for all variables. The results of this analysis, presented in column (3), demonstrate a high degree of consistency with our benchmark regression outcomes. These comprehensive robustness checks collectively reinforce the stability and reliability of our primary findings, providing strong support for the significant impact of e-commerce on HQAD.

4.3.2 Endogenous processing

To address potential endogeneity issues in our regression analysis, we employed a series of instrumental variables (IVs). Our IVs included the lagged e-commerce index, an interaction term between a historical variable and the 1987 time trend of telephone ownership per 100 residents (Huang et al., 2019), and the mean e-commerce development level of neighboring provinces. The validity of these IVs was rigorously tested. Wald statistic results rejected the null hypothesis of "no correlation with endogenous variables" at the 10% significance level, indicating our IVs are not weak. Additionally, the overidentification test failed to reject the null hypothesis of "exogenous instrumental variables" at the 10% level, satisfying the exogeneity condition. Upon addressing potential bidirectional causality through our IV approach, we observed a substantial increase in the e-commerce impact coefficient. The results of this instrumental variable regression analysis, presented in columns 1, 2, and 3 of Table 6, provide robust evidence for the causal relationship between e-commerce and our dependent variable.

4.3.3 Heterogeneity analysis

The spatial heterogeneity of agricultural development, intrinsically linked to geographical location and natural resource endowments, suggests potential regional variations in the impact of e-commerce on HQAD across China's diverse landscape. Our econometric analysis, presented in columns (1)–(4) of Table 7, provides empirical evidence of these regional disparities. The results indicate that the Central region of China experiences the most pronounced effect of e-commerce on HQAD, with the largest coefficient of 1.064, significant at the 1% level. Similarly, the Northeastern and Western regions demonstrate substantial impacts, with coefficients of 0.466 and 0.153, significant at the 1 and 5% levels, respectively. In contrast, the Eastern region exhibits a comparatively smaller, albeit still significant, impact with a coefficient of 0.024. These regional disparities may be attributed to the varying degrees of constraints faced by different areas in terms of geographical conditions, infrastructure development, and access to consumer markets. The Central, Western, and Northeastern regions, which traditionally face more significant barriers in these aspects compared to the more developed Eastern region, appear to benefit more substantially from e-commerce. This technology effectively mitigates geographical limitations by facilitating cross-regional flows of agricultural products and production factors, consequently emerging as a particularly potent driver of HQAD in these regions. This finding corroborates the recent work of Yang et al. (2023), who similarly observed differential impacts of e-commerce across China's diverse geographical landscape.

TABLE 3 Descriptive analysis of relevant variables.

Variable	Observation	Average	Standard error	Minimum value	Maximum value
HQAD	660	0.3447	0.0784	0.1803	0.5858
E-commerce	660	0.2058	0.1969	0.0315	0.8494
Rate of disaster-affected crop	660	0.1562	0.1007	0.0146	0.4903
Foreign direct investment	660	0.0483	0.0538	0.0059	0.3683
Financial development level	660	1.8504	1.7975	0.4113	9.4376
Macroeconomic environment	660	0.8411	0.1919	0.0044	0.9964
The agricultural tax is concealed	660	0.7273	0.4457	0	1
Density of rural road	660	0.0497	0.0573	0.0010	0.2807

TABLE 4 Benchmark regression of e-commerce impact effects.

	(1)	(2)	(3)	(4)
Variables	HQAD	HQAD	HQAD	HQAD
E-commerce	0.1462***	0.1465***	0.1518**	0.1470***
	(0.0143)	(0.0147)	(0.0612)	(0.0537)
Rate of disaster-affected crop				−0.0630***
				(0.0168)
Level of foreign direct investment				−0.0238
				(0.0338)
Financial development level				0.0080***
				(0.0024)
Macroeconomic environment				0.1045
				(0.0731)
The agricultural tax is concealed				0.1206**
				(0.0588)
Density of rural road				0.2548***
				(0.0550)
Area fixed	No	Yes	Yes	Yes
Time fixed	No	No	Yes	Yes
Constant	0.3146***	0.3094***	0.3288***	0.1886**
	(0.0044)	(0.0135)	(0.0489)	(0.0804)
Observations	660	660	660	660
R-squared	0.135	0.146	0.884	0.900

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

TABLE 5 Robustness test results.

	(1)	(2)	(3)
Variables	HQAD (Principal component analysis)	HQAD	HQAD
E-commerce (Principal component analysis)	0.0467***		
	(0.0092)		
E-commerce		0.1394***	0.1388 ***
		(0.0187)	(0.0532)
Control variable	Control	Control	Control
Area fixed	Yes	No	Yes
Time fixed	Yes	No	Yes
Joint fixed effect of year and province	No	Yes	No
R-squared	0.903	0.351	0.901

*** indicate significance at the 1% levels.

4.4 Mechanism analysis

Drawing upon our theoretical framework, we developed four mediating indicators to investigate the potential pathways through which e-commerce influences HQAD. (1) Online trading volume of agricultural products (TVAP), derived by multiplying the scale of annual agricultural product transactions by the provincial ratio of e-commerce transactions to the national total, with logarithmic transformation applied to mitigate heteroscedasticity; (2) Modernization degree of agricultural industry chain (MDAIC), constructed using a five-dimensional indicator system encompassing integrated development, innovation and upgrading, global cohesion, policy coordination, and stable operation; (3) Socialized service level (SSL), computed from the input index of the service industry in agriculture, forestry, animal husbandry, and fishery as reported in provincial input–output tables, with linear interpolation employed to address missing data; and (4) Supply degree of agricultural infrastructure (SDAI), utilizing the length of long-distance fiber optic cable lines in rural and urban areas as a proxy for digital infrastructure supply, given its critical role in e-commerce development and fundamental importance to HQAD.

To empirically examine the hypothesized mediating pathways, we employed a parallel mediation effect model framework. This approach extends the baseline model (Equation 7) to incorporate the potential mediating variables, allowing for a more nuanced analysis of the mechanisms through which e-commerce influences HQAD. The expanded model is specified as follows.

$$\mathrm{TVAP}_{it} = \beta_{10} + \beta_{11} ec_{it} + \sum_{j=1}^{n} \lambda_{1j} X_{jit} + \delta_{1i} + \mu_{1t} + \varepsilon_{1it} \quad (8)$$

$$\mathrm{MDAIC}_{it} = \beta_{20} + \beta_{21} ec_{it} + \sum_{j=1}^{n} \lambda_{2j} X_{jit} + \delta_{2i} + \mu_{2t} + \varepsilon_{2it} \quad (9)$$

TABLE 6 Regression results of endogenous processing.

HQAD	(1)	(2)	(3)
	Lag period of e-commerce index	Number of telephones owned per million people in 1987	Space proximity tool variable
E-commerce	0.2395**	1.5863***	1.2581***
	(0.1007)	(0.2228)	(0.3401)
Rate of disaster-affected crop	−0.0595***	−0.0790***	−0.0887***
	(0.0167)	(0.0165)	(0.0161)
Control variable	Control	Control	Control
Kleibergen-Paap rk LM	187.526	52.705	10.983
Kleibergen-Paap rk F	242.845	52.245	10.141
Constant	0.1306	−0.6334***	−0.6957***
	(0.1010)	(0.1388)	(0.1907)
Observations	630	660	572
R-squared	0.901	0.913	0.920

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

$$\mathrm{SSL}_{it} = \beta_{30} + \beta_{31}ec_{it} + \sum_{j=1}^{n}\lambda_{3j}X_{jit} + \delta_{3i} + \mu_{3t} + \varepsilon_{3it} \quad (10)$$

$$\mathrm{SDAI}_{it} = \beta_{40} + \beta_{41}ec_{it} + \sum_{j=1}^{n}\lambda_{4j}X_{jit} + \delta_{4i} + \mu_{4t} + \varepsilon_{4it} \quad (11)$$

$$\begin{aligned}\mathrm{quality}_{it} &= \gamma_0 + \gamma_1\mathrm{ec}_{it} + \gamma_2\mathrm{TVAP}_{it} + \gamma_3\mathrm{MDAIC}_{it} \\ &+ \gamma_4\mathrm{SSL}_{it} + \gamma_5\mathrm{SDAI}_{it} + \lambda_j\sum_{i=1}^{n}X_{jit} + \delta_i + \mu_t + \varepsilon_{it} \quad (12)\end{aligned}$$

Equations 8–11 measure the relationship between explanatory variables and mediating variables. Equation 12 examines the relationship among explanatory variables, mediating variables, and the explained variable.

Adopting Hayes (2013) approach, this study utilized 5,000 bootstrap samples and the PROCESS macro model 4 in SPSS, with a 95% bias-corrected confidence interval (CI) to analyze the parallel mediating effects of e-commerce on HQAD. Bootstrap sampling, not relying on assumptions about the sampling distribution, is the most effective method for assessing mediating effects. A statistically significant indirect effect is indicated if the CI range excludes zero, suggesting the presence of a mediating effect (Wang, 2024). Table 8 presents the coefficients of multiple parallel mediating regressions, examining the direct and indirect effects of e-commerce on HQAD through various mediators. The results indicate a significant direct positive effect of e-commerce on HQAD, with a coefficient of 0.2173 at the 1% significance level, suggesting that e-commerce contributes to HQAD even when considering mediating factors. Furthermore, we found there exist significant positive relationships between e-commerce and four mediating variables at the 1% significance level. This implies that e-commerce development enhances these aspects of the agricultural sector. Additionally, all four mediating variables demonstrate positive effects on HQAD. These findings suggest that each mediator plays a role in transmitting e-commerce's effects on HQAD. Table 9 reveals the parallel mediating effects of e-commerce on HQAD, with all variables showing significant indirect effects. Market expansion (TVAP) demonstrates the strongest mediating effect, accounting for 43.27% of the total effect, highlighting its crucial role in fostering HQAD through e-commerce. The modernization of the agricultural industry chain (MDAIC) follows, contributing 14.18% to the total effect, emphasizing the importance of industry chain upgrades. The socialized service level (SSL) also plays a notable role, accounting for 3.31% of the total effect, underscoring the significance of improved agricultural services. The supply of agricultural infrastructure (SDAI) shows the smallest mediating effect, suggesting that while important, it may have less immediate impact on HQAD compared to other factors. Significant differences are observed between the mediating effect of TVAP and those of SSL, MDAIC, and SDAI, providing a nuanced understanding of the complex relationships within this e-commerce-driven developmental process.

5 Discussion

This study's key findings reveal that e-commerce significantly promotes HQAD in China through four pathways: market expansion, agricultural industry chain modernization, social service optimization, and infrastructure supply. Notably, market expansion exhibits the strongest mediating effect (43.27%), followed by industry chain modernization (14.18%). These results extend previous research by Han et al. (2023) on e-commerce's role in green agriculture and Bai et al. (2024) on consumer behavior, while challenging traditional supply-side dominant perspectives by emphasizing demand-side factors in driving HQAD. Theoretically, this study advances existing frameworks by proposing a "demand-driven supply adjustment" model, integrating both demand and supply-side factors, and employing a multi-pathway analysis to uncover the complex mechanisms of e-commerce's impact on HQAD. This approach not only enriches agricultural economics theory but also provides a new paradigm for studying digital transformation in other economic sectors. Practically, these findings offer valuable insights for agricultural policy-making and e-commerce development strategies. They suggest the need for policies supporting rural digital infrastructure, e-commerce training, and the optimization of industry chain integration and social services. Furthermore, the comprehensive framework developed for assessing agricultural development quality can aid governments and relevant institutions in more accurately monitoring and evaluating agricultural progress, thereby informing more targeted development strategies.

6 Conclusions and policy implications

This study constructs a comprehensive evaluation system for HQAD in China and investigates the impact of e-commerce on HQAD using provincial panel data from 2000 to 2021. By employing mediating effect models, we examine the multiple pathways through which e-commerce influences HQAD. Our findings contribute to the existing literature and offer important policy implications. The main conclusions are as follows: Firstly, e-commerce significantly promotes HQAD in China, with a positive impact coefficient of 0.147. This finding aligns with Chen et al. (2022), who reported that e-commerce adoption enhances technical efficiency in wheat production. However, our study extends beyond a single crop to encompass overall agricultural development. Secondly, the impact of e-commerce on HQAD varies across regions. The Central region of China experiences the largest impact (coefficient: 1.064), followed by the Northeastern (0.466) and Western (0.153) regions, while the Eastern region shows the smallest impact (0.024). This regional heterogeneity

TABLE 7 Regional heterogeneity in the impact of e-commerce on HQAD.

Variables	HQAD			
	(1)	(2)	(3)	(4)
	Eastern Region	Central Region	Western Region	Northeastern Region
E-commerce	0.024***	1.064***	0.153**	0.466***
	(2.89)	(13.70)	(2.56)	(5.82)
Control variables	Control	Control	Control	Control
_cons	0.450***	0.237***	0.347***	0.240***
	(13.06)	(13.11)	(9.49)	(15.59)
Area fixed	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes
N	220	132	242	66
R-squared	0.1947	0.6751	0.1912	0.9062

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

TABLE 8 Regression coefficients of E-commerce and mediating variables on HQAD.

Variables	(1)	(2)	(3)	(4)	(5)
	TVAP	MDAIC	SSL	SDAI	HQAD
E-commerce	4.8512*** (0.2168)	0.2485*** (0.0292)	0.3487*** (0.0584)	3.7922*** (0.3198)	0.2173*** (0.0215)
TVAP					0.0179*** (0.0033)
MDAIC					0.0585** (0.0269)
SSL					0.0363*** (0.0113)
SDAI					0.0026* (0.0022)
Control variables	Control	Control	Control	Control	Control
Area fixed	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes
N	660	660	660	660	660
R-squared	0.5796	0.3205	0.0822	0.3427	0.3076

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

TABLE 9 Parallel mediating effects of e-commerce on HQAD.

Variables	HQAD				
	(1)	(2)	(3)	(4)	(5)
	Coefficient	BootSE	BootLLCI	BootULCI	Proportion relative mediated
Total indirect	0.1035	0.016	0.074	0.1375	62.20%
Indirect 1 TVAP	0.072	0.014	0.0444	0.0992	43.27%
Indirect 2 MDAIC	0.0236	0.0118	0.0012	0.0483	14.18%
Indirect 3 SSL	0.0055	0.0027	0.0011	0.0117	3.31%
Indirect 4 SDAI	0.0025	0.0024	0.0008	0.0078	1.50%
SSL – mdaic	−0.0181	0.0119	−0.0425	0.0052	
SSL – TVAP	−0.0666	0.0143	−0.0943	−0.0384	
SSL – SDAI	0.003	0.0032	−0.0029	0.0099	
MDAIC – TVAP	−0.0485	0.0208	−0.0886	−0.0067	
MDAIC – SDAI	0.0211	0.0124	−0.0025	0.0464	
TVAP – SDAI	0.0696	0.0139	0.0423	0.0966	

adds nuance to the findings of Yang et al. (2023), who focused on the national-level impact of agricultural R&D on HQAD. Lastly, e-commerce drives HQAD through four main pathways: market expansion (43.27% of total effect), modernization of the agricultural industry chain (14.18%), optimization of agricultural social services (3.31%), and supply of agricultural infrastructure (1.50%). This multi-pathway analysis provides a more comprehensive understanding compared to previous studies like Zhong et al. (2022), which primarily focused on the digital economy's impact on agricultural technological progress. The market expansion effect of e-commerce is the most prominent, highlighting the crucial role of demand-side factors in driving HQAD. This finding challenges the traditional supply-side dominant perspectives in agricultural development research.

Based on these findings, several policy implications are derived. As a developing country with a large agricultural sector, (1) Given that the impact of e-commerce on HQAD shows significant heterogeneity across different regions, policymakers should formulate differentiated e-commerce development strategies based on the specific conditions and characteristics of each region. This approach aims to fully leverage the potential of e-commerce in promoting HQAD and ensure that each region can maximize the benefits brought by e-commerce according to its own circumstances. (2) The study indicates that market expansion is the primary pathway through which e-commerce promotes HQAD. Therefore, policymakers should prioritize supporting the construction and optimization of agricultural e-commerce platforms, encourage the development of diverse e-commerce models such as live-streaming sales and community marketing. Simultaneously, the rural logistics system should be improved to reduce agricultural product circulation costs. Furthermore, policies should support cross-regional e-commerce cooperation, breaking geographical limitations to achieve nationwide and even international sales of agricultural products. (3) This research finds that agricultural industry chain modernization is the second most significant pathway through which e-commerce impacts HQAD. Therefore, policies should encourage vertical integration of the agricultural industry chain, support the development of agricultural cooperatives, and promote the application of digital technologies throughout the supply chain. Specific measures may include providing tax incentives to support agricultural industry chain integration, establishing special funds to support agricultural cooperatives in developing e-commerce, and organizing training programs to enhance farmers' digital skills. (4) Although this study shows that agricultural socialized services and infrastructure demonstrated smaller mediating effects, they are crucial for long-term agricultural development. Therefore, policies should focus on improving rural digital infrastructure, such as accelerating 5G network coverage in rural areas and providing inclusive internet access services. Concurrently, e-commerce training for farmers should be strengthened, and the digitalization level of agricultural extension services should be enhanced. Additionally, policies should support the development of smart agriculture, such as promoting the application of Internet of Things (IoT) and big data technologies in agricultural production.

Through mediation analysis, this study contributes to establishing a comprehensive "demand-driven supply adjustment" framework, offering valuable insights for future researchers. However, the research has some limitations. Firstly, due to data constraints, the HQAD evaluation system may not fully capture all dimensions, suggesting that future studies could incorporate more comprehensive indicators. Secondly, this paper extensively explores the impact of e-commerce development, with future research delving into new transformations brought by next-generation digital technologies like the Internet of Things and blockchain, deepening the understanding of e-commerce impact. Lastly, the mediating effect model may not encompass all influencing paths of e-commerce. Subsequent research should integrate theoretical analysis with China's specific conditions, considering regional development disparities to further investigate other potential mechanisms and various adaptation scenarios.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the datasets used during the current study are available from the first author on reasonable request. Requests to access these datasets should be directed to YK, 20166228@sdufe.edu.cn.

Author contributions

YK: Conceptualization, Formal analysis, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. XZ: Formal analysis, Investigation, Resources, Writing – review & editing. XL: Data curation, Methodology, Writing – original draft. PP: Funding acquisition, Methodology, Resources, Supervision, Visualization, Writing – review & editing, Writing – original draft. JL: Resources, Validation, Writing – review & editing. CF: Investigation, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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