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Rural e-commerce and agricultural supply chain integration: A panel data analysis of China's rural development

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Abstract: This study examines the impact of rural e-commerce development on the integration of agricultural supply chains in China, utilizing panel data from 27 provincial-level regions from 2016 to 2023. By constructing a dynamic panel model and employing the System Generalized Method of Moments (System GMM), we analyze how rural e-commerce infrastructure and logistics efficiency influence supply chain integration. The empirical results reveal that improvements in rural e-commerce infrastructure and logistics efficiency significantly enhance the integration of agricultural supply chains. Specifically, increases in rural e-commerce infrastructure and logistics efficiency lead to notable improvements in supply chain integration. Heterogeneity analysis indicates that these effects are more pronounced in economically less developed regions and western areas of China. Based on these findings, we propose policy recommendations, including increasing investment in rural e-commerce infrastructure, enhancing logistics efficiency through technological advancements, implementing region-specific policies to address local needs, strengthening rural logistics networks, and fostering collaborative supply chain ecosystems. This research contributes to the literature by providing updated empirical evidence on the role of rural e-commerce in agricultural supply chain integration and offers practical insights for policymakers aiming to promote rural revitalization and sustainable agricultural development in China.

Keywords: Rural e-commerce; Agricultural supply chain integration; System GMM; Logistics efficiency; Rural revitalization

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1 Introduction

In recent years, China has undergone a strategic transition from rapid economic growth to a focus on high-quality development, positioning rural revitalization as a cornerstone of national policy aimed at transforming and upgrading the rural economy. This strategic emphasis seeks to address long-standing challenges that have impeded agricultural development and hindered rural prosperity. The traditional agricultural supply chain in China is beset with numerous obstacles, including information asymmetry, high logistics costs, fragmented distribution channels, and low circulation efficiency. These issues not only disrupt the seamless flow of agricultural products from producers to consumers but also restrict market access for farmers, ultimately limiting their income growth and contributing to rural economic stagnation.

Information asymmetry in the agricultural sector often leads to a mismatch between supply and demand, resulting in price fluctuations and inefficient resource allocation. Farmers may lack access to accurate market information regarding consumer preferences, pricing trends, and demand forecasts, hindering their ability to make informed production decisions. Concurrently, consumers may have limited knowledge about the origin, quality, and safety of agricultural products, affecting their purchasing choices and potentially undermining trust in domestic agricultural goods.

High logistics costs further exacerbate these challenges. The transportation of agricultural products, especially perishable goods, requires efficient and reliable logistics networks. In many rural areas, inadequate transportation infrastructure and the absence of advanced logistics services lead to delays, increased spoilage rates, and higher costs. These factors diminish the competitiveness of agricultural products in both domestic and international markets and erode profit margins for farmers, making it difficult for them to reinvest in their operations or adopt new technologies.

Fragmented distribution channels contribute significantly to the inefficiency of the agricultural supply chain. The presence of multiple intermediaries between farmers and consumers inflates transaction costs and reduces price transparency. Each intermediary adds a markup to the product, diminishing the share of the final price that reaches the producers. This fragmentation complicates quality control and traceability efforts, as products change hands multiple times before reaching the end consumer, making it challenging to ensure product safety and consistency.

Low circulation efficiency is a direct consequence of the aforementioned factors and manifests in slow turnover rates and limited market reach. Farmers often rely on traditional, localised markets, which restricts their ability to access larger, more lucrative markets both domestically and internationally. This limitation hinders economies of scale and prevents farmers from capitalising on broader market opportunities, thereby stifling rural economic growth and development.

The advancement of rural e-commerce, propelled by rapid developments in internet technologies and the proliferation of e-commerce platforms, presents new opportunities for overcoming these entrenched challenges. Platforms such as Alibaba's Taobao, JD.com, and Pinduoduo have revolutionised the marketing and distribution of agricultural products by enabling direct connections between farmers and consumers. This digital transformation reduces reliance on traditional intermediaries, thereby lowering transaction costs and increasing price transparency. Through e-commerce platforms, farmers can access real-time market information, allowing them to adjust production strategies in response to consumer demand and pricing trends. This direct engagement not only enhances market efficiency but also empowers farmers to take greater control over their supply chains.

By bypassing intermediaries, farmers can retain a larger portion of the profits, which contributes to income growth and incentivises further investment in quality and productivity improvements. Additionally, e-commerce platforms often provide tools and services that assist farmers with branding, marketing, and customer relationship management, further enhancing their competitive advantage. The use of data analytics and consumer feedback mechanisms enables farmers to better understand market trends and consumer preferences, facilitating more strategic decision-making.

Moreover, rural e-commerce plays a significant role in creating new avenues for entrepreneurship and employment among rural residents, contributing to poverty alleviation and aligning with the broader goals of rural revitalisation. The digital economy facilitates the development of ancillary services such as online marketing, digital payment systems, and logistics

support, generating employment opportunities beyond traditional farming activities. This diversification of the rural economy not only improves livelihoods but also helps stem rural-to-urban migration by providing viable economic opportunities within rural communities.

Despite the promising potential of rural e-commerce to transform agricultural supply chains and stimulate rural development, there is a notable lack of empirical studies that quantitatively analyse its impact, particularly concerning the roles of e-commerce infrastructure and logistics efficiency. Existing research often focuses on theoretical discussions or case studies limited to specific regions, which may not capture the diverse regional variations across China. Furthermore, many studies do not employ advanced econometric models or utilise recent data, limiting the generalisability and applicability of their findings. This gap in the literature underscores the need for large-scale empirical analyses that provide a comprehensive understanding of how rural e-commerce influences agricultural supply chain integration on a national scale.

To address this gap, the present study examines how the development of rural e-commerce infrastructure impacts the integration of agricultural supply chains in China. Specifically, we investigate the role of logistics efficiency in enhancing agricultural supply chain integration within the context of rural e-commerce. By utilising panel data from 27 provincial-level regions in China from 2016 to 2023 and employing a dynamic panel model with the System Generalised Method of Moments (System GMM) estimator, this study offers robust empirical evidence and practical insights into the mechanisms at play.

Agricultural supply chain integration refers to the coordination and collaboration among various stakeholders—farmers, processors, distributors, and retailers—to optimize the flow of products from production to consumption. Enhanced integration can lead to improved efficiency, reduced costs, and increased responsiveness to market demands. Rural e-commerce has the potential to facilitate this integration by providing digital platforms for communication, transaction, and information sharing. By streamlining processes and improving connectivity among supply chain participants, e-commerce platforms can mitigate some of the structural inefficiencies that have historically plagued the agricultural sector.

Logistics efficiency is a critical component of supply chain integration, particularly in the agricultural sector where timely delivery and product quality are paramount. Efficient logistics networks can reduce transportation times, minimise spoilage, and lower costs, thereby enhancing the overall performance of the supply chain. Understanding the interplay between rural e-commerce and logistics efficiency is essential for developing strategies to improve supply chain integration. Improvements in logistics not only benefit farmers by reducing costs and losses but also enhance customer satisfaction by ensuring timely delivery of fresh products.

Additionally, the study examines the impact of government agricultural subsidies and rural consumption capacity on agricultural supply chain integration. Government subsidies can incentivise farmers to innovate and improve by reducing production costs and risks, thus enhancing the efficiency and quality of agricultural production. Rural consumption capacity reflects the purchasing power and consumption tendencies of rural residents; its increase can stimulate demand for agricultural products, further promoting supply chain integration and development. By incorporating these control variables, we aim to provide a more comprehensive understanding of the factors influencing agricultural supply chain integration and offer richer empirical evidence for policymakers.

By conducting this study, we contribute to the literature by filling the existing research gap and providing evidence-based policy recommendations. Our findings can inform government initiatives aimed at supporting the development of agricultural supply chains and facilitating the implementation of the rural revitalisation strategy. Specifically, we offer insights into how investments in e-commerce infrastructure, logistics networks, government subsidies, and consumption capacity can yield significant benefits for rural economies. These insights are particularly relevant for policymakers seeking to promote inclusive growth and reduce regional disparities.

The remainder of this paper is organised as follows. We first provide a comprehensive literature review on rural e-commerce and agricultural supply chain integration, highlighting key findings from previous studies and identifying areas that require further exploration. This review sets the foundation for our theoretical framework by contextualising the current state of research and pinpointing the contributions our study aims to make. Next, we develop the theoretical framework and explore

the mechanisms through which rural e-commerce integrates with agricultural supply chains, grounding our analysis in established economic theories and supply chain management principles. Subsequently, we outline the methodology of our study, detailing the data sources, variable definitions, and empirical model specification. We discuss the rationale behind our methodological choices, including the use of the System GMM estimator to address potential endogeneity issues and the selection of variables to accurately capture the constructs of interest. Following the methodology, we present the empirical results and discuss the findings in relation to our hypotheses and the existing literature. We interpret the results, assess their robustness through various diagnostic tests and alternative model specifications, and consider their implications for theory and practice. Finally, we conclude the paper by summarising the key insights from our research and offering policy recommendations. We acknowledge the limitations of our study, such as data constraints and potential measurement errors, and suggest directions for future research that can build upon our findings. Through this comprehensive analysis, we aim to advance the understanding of the impact of rural e-commerce on agricultural supply chain integration in China and contribute to the broader discourse on rural development and economic transformation. Our study not only provides empirical evidence of the benefits of rural e-commerce but also offers practical guidance for stakeholders seeking to leverage digital technologies to enhance agricultural supply chains.

2 Literature Review

The integration of e-commerce with agricultural supply chains has garnered extensive academic attention due to its potential to transform rural economies and enhance supply chain efficiency. This section provides a comprehensive review of the existing literature, identifying key themes, debates, and gaps that inform the present study.

2.1 E-commerce and Supply Chain Efficiency

Numerous studies have emphasized the pivotal role of e-commerce in enhancing supply chain efficiency by reducing transaction costs, simplifying distribution channels, and improving market responsiveness. Kumar and Narayan(2021) argue that e-commerce platforms facilitate direct interactions between producers and consumers, reducing intermediaries and thereby lowering costs This direct linkage not only reduces the time required for products to reach consumers but also enhances the agility of supply chains in responding to market demand fluctuations. Moreover, e-commerce platforms provide real-time market information, enabling farmers to make more accurate demand forecasts and adjust their production plans accordingly, reducing inventory backlogs and waste.

Wang et al. (2022) demonstrate that adopting e-commerce in rural areas increases supply chain flexibility, allowing farmers to adjust production based on real-time market information. Such flexibility is crucial for perishable agricultural products, where timing is essential to maintain quality and meet consumer demand. However, Reardon et al. (2012) cautioned that the benefits of e-commerce are not uniformly distributed. Smallholder farmers often face barriers such as limited digital literacy, inadequate funding, and underdeveloped infrastructure, which can exacerbate existing inequalities in rural areas, preventing some farmers from fully leveraging the opportunities presented by e-commerce.

Li and Wang (2021) explored how e-commerce promotes supply chain synergy. They found that e-commerce platforms strengthen information sharing and collaboration among supply chain participants, enhancing overall efficiency and competitiveness. The integration facilitated by e-commerce platforms allows for better coordination in production planning, inventory management, and distribution. However, they also noted that trust among supply chain parties and data security issues need to be addressed. Establishing robust mechanisms to protect data privacy and ensure information security is essential for fostering collaboration and building trust.

Qin et al. (2023) examined the causal relationship between rural e-commerce and county-level economic development in China through a quasi-natural experiment based on the national rural e-commerce comprehensive demonstration policy. Their findings indicated that the policy had a positive effect on county-level GDP, increasing it by 3.5% (0.7% annually). This impact was particularly significant in areas such as industrial structure optimization and non-agricultural employment, highlighting the importance of infrastructure improvement in facilitating e-commerce development in rural areas.

2.2 Logistics Efficiency and Cold Chain Management

Logistics efficiency, particularly in cold chain management, is critical for the distribution of perishable agricultural products. Flynn (2020) emphasizes that integrating e-commerce with advanced logistics systems, including cold chain technologies, can significantly reduce spoilage and maintain product quality. The ability to deliver fresh products promptly not only enhances consumer satisfaction but also expands market opportunities for farmers, enabling them to access high-end markets and meet urban consumer demand.

Conversely, Feng (2021) highlighted the high costs of cold chain logistics as a major barrier for small-scale farmers. They advocated for government support and public-private partnerships to alleviate these costs and promote the widespread adoption of cold chain technologies. Additionally, Yang and Chen (2022) underscored the need for standardized logistics practices to ensure consistency and reliability across the supply chain. Standardization can mitigate product quality issues caused by improper handling and improve overall supply chain efficiency.

Wang et al. (2022) pointed out that inadequate logistics infrastructure in rural areas—such as poor road conditions and outdated transportation equipment—is a significant factor constraining logistics efficiency. They suggested that governments should increase investment in rural transportation infrastructure to enhance the coverage and service quality of logistics networks, thereby supporting e-commerce development. Improved infrastructure can reduce transportation times and costs, making rural agricultural products more competitive.

Dong et al. (2023) investigated how the digital economy promotes low-carbon development in China, particularly through the e-commerce city pilot reform. Their findings indicated that integrating e-commerce with modern logistics could effectively reduce carbon emissions and improve logistics efficiency, which has significant implications for the integration of agricultural supply chains in China.

2.3 Information Transparency and Traceability

Improving information transparency and product traceability through e-commerce platforms has been identified as a key factor in building consumer trust and enhancing the value of agricultural products. Aung et al. (2014) discuss how blockchain technology can enhance traceability in food supply chains, providing consumers with verifiable information about product origins, production processes, and logistics links.

Kshetri (2021) supported this view, suggesting that blockchain can reduce information asymmetry and prevent fraudulent activities, thereby improving supply chain transparency. Despite the potential benefits, Yadlapalli (2021) noted practical challenges in implementing such technologies, including data privacy concerns, scalability issues, and the need for standardized protocols. Lin et al. (2021) also pointed out that while consumers value transparency, they may not always be willing to pay a premium for it, affecting the return on investment for farmers and e-commerce platforms.

Zhang et al. (2021) highlighted the importance of education and training in increasing the adoption rate of information technologies. They found that a lack of understanding and skills regarding new technologies is a major barrier preventing farmers from utilizing information systems to enhance supply chain transparency. Addressing this skills gap is essential for maximizing the benefits of technological advancements.

Liu et al. (2023) conducted an empirical study showing that rural e-commerce development not only improves information transparency and consumer trust but also contributes to rural economic growth. The study indicated that rural e-commerce significantly improves supply chain transparency, particularly in enhancing agricultural product quality and consumer trust.

2.4 Rural E-commerce, Government Agricultural Subsidies, and Rural Consumption Capacity

Rural e-commerce is seen as a catalyst for rural revitalization by creating employment opportunities, stimulating economic growth, and improving quality of life, thereby promoting sustainable development in rural areas. Liu et al. (2023) found that e-commerce participation contributes to poverty reduction by increasing income levels and diversifying income sources for rural households. Yang et al. (2022) observed that regions with higher e-commerce penetration experienced significant improvements in rural living standards and infrastructure development, driving the transformation and upgrading of rural

economies.

Wang et al. (2021) argued that without adequate infrastructure and training, rural e-commerce initiatives may not achieve their intended outcomes. They emphasized the importance of comprehensive strategies, including investments in physical infrastructure (such as internet and transportation), education (improving digital literacy), and supportive policies (such as financial incentives and technical support), to address structural challenges. Feng (2021) suggested that government support in policy formulation, regulatory frameworks, and resource allocation is crucial for the successful implementation of e-commerce in rural areas.

Government agricultural subsidies play a crucial role in supporting rural farmers by reducing production costs and encouraging investments in productivity-enhancing technologies. Zhang et al. (2022) showed that subsidies can alleviate financial constraints for farmers, enabling them to adopt modern agricultural practices and integrate more effectively into supply chains. Government subsidies are particularly important for smallholder farmers who may struggle to compete in an increasingly digitalized market.

Rural consumption capacity reflects the purchasing power of rural residents, which is also crucial to the success of rural e-commerce. Li and Wang (2021) indicated that increased rural consumption capacity can stimulate demand for agricultural products and related services, strengthening the agricultural supply chain. Increased consumption capacity can spark market activity and drive greater economic participation in rural areas, creating a virtuous cycle that benefits both producers and consumers.

Qin et al. (2023) emphasized that the proliferation of information and communication technology in rural areas has made rural e-commerce an emerging economic phenomenon in China. Their study demonstrated the positive impact of e-commerce policies on county-level economies, particularly in infrastructure development, industrial restructuring, and non-agricultural employment.

Li et al. (2023) also noted that government-led rural e-commerce development can effectively help alleviate poverty in rural areas, particularly by increasing household income, creating job opportunities, and improving living standards.

2.5 Synthesis and Research Implications

While existing literature provides valuable insights into the role of e-commerce in enhancing supply chain efficiency, logistics management, information transparency, and promoting rural revitalization, several areas warrant further investigation.

Firstly, many studies are confined to case analyses or specific regions, limiting the generalizability of their findings. Significant disparities exist among different regions in China regarding economic development levels, infrastructure conditions, and policy environments. Consequently, research that encompasses a broader range of regions is essential to understand wider patterns and impacts across the country.

Secondly, most existing research employs cross-sectional data or qualitative methods, which fail to capture the dynamic changes and lagged effects associated with supply chain integration and e-commerce development over time. Employing panel data and dynamic models could reveal temporal relationships and provide a more nuanced understanding of how these factors evolve, offering insights into the long-term impacts of policy and market changes.

Moreover, potential endogeneity issues—such as the bidirectional causal relationship between e-commerce development and supply chain integration—are often overlooked. Ignoring endogeneity can lead to biased estimation results, thereby affecting the reliability of conclusions and undermining the effectiveness of subsequent policy recommendations. Addressing these methodological concerns is crucial for producing robust and credible findings.

Lastly, there is a notable lack of research that translates empirical findings into actionable policy recommendations, particularly within the context of China's rural revitalization strategy. This gap limits the practical applicability of academic studies and hinders the formulation of policies that could effectively harness e-commerce to drive rural development. There is a pressing need for studies that not only analyze data but also provide clear guidance for policymakers.

In light of these gaps, future research should focus on large-scale empirical analyses utilizing recent data and advanced econometric models to account for regional diversity and temporal dynamics. Such studies should aim to address endogeneity

concerns through appropriate methodological approaches, enhancing the validity of their findings. By doing so, researchers can contribute to a more comprehensive understanding of the mechanisms through which rural e-commerce influences agricultural supply chain integration.

Furthermore, integrating empirical findings with policy formulation is essential to maximize the economic and social benefits of rural e-commerce. By providing evidence-based recommendations, future studies can support the coordinated development of rural e-commerce and supply chains, ultimately promoting sustainable rural development and aiding in the successful implementation of rural revitalization initiatives in China.

3 Analysis of the Mechanisms and Operating Models

The integration of rural e-commerce with agricultural supply chains represents a transformative shift in China's agricultural sector, reshaping the production, distribution, and consumption of agricultural products. Through the use of digital technologies, rural e-commerce enhances efficiency, reduces transaction costs, and improves market access for rural producers. Understanding the mechanisms through which rural e-commerce influences agricultural supply chain integration is essential for comprehending its impact on rural economies.

3.1 Mechanisms of Integration between Rural E-commerce and Agricultural Supply Chains

One of the primary mechanisms is the integration of network channels. Rural e-commerce platforms have revolutionized traditional marketing by establishing direct links between agricultural producers and consumers. These platforms serve as virtual marketplaces where farmers can showcase their products beyond geographical constraints. The elimination of multiple intermediaries, who traditionally inflated transaction costs and extended product delivery times, allows farmers to receive a larger share of the final price. This direct engagement not only reduces costs but also provides farmers with immediate market feedback, enabling them to adjust production strategies in response to consumer preferences and demand trends. For instance, platforms like Taobao and Pinduoduo enable farmers to sell directly to a vast consumer base, facilitating branding efforts that highlight unique attributes such as organic practices or geographical indications, thus adding value to their offerings.

Another critical mechanism is the integration of logistics networks. Efficient logistics are essential for the successful integration of agricultural supply chains, particularly given the perishable nature of many agricultural products. Rural e-commerce has spurred significant advancements in logistics, addressing longstanding challenges related to transportation and distribution in rural areas. Collaborations between e-commerce platforms and logistics providers have led to the development of sophisticated logistics networks, including regional distribution centers and optimized delivery routes through data analytics. The integration of cold chain logistics has been transformative for fresh agricultural products, ensuring quality and freshness throughout transportation. Partnerships like that between Alibaba's Cainiao Network and rural cooperatives have improved last-mile delivery services in remote areas, leveraging technologies such as GPS tracking and real-time data monitoring to enhance reliability and efficiency.

The integration of information systems constitutes another vital mechanism. Advanced information technologies introduced by e-commerce platforms have improved visibility, traceability, and decision-making within the supply chain. Integrated information systems allow farmers to access market information, consumer preferences, and price trends, facilitating informed production decisions. Predictive analytics enable adjustments in planting schedules or crop selection based on anticipated demand, aligning supply with market needs and reducing overproduction and waste. Information systems also enhance traceability—a growing consumer concern regarding food safety and quality. Technologies like QR codes and blockchain provide end-to-end visibility of the product journey from farm to table, building consumer trust and justifying premium pricing for verified products. Improved information flow fosters better coordination among supply chain actors, as suppliers, logistics providers, and retailers can synchronize activities based on shared data, reducing delays and enhancing efficiency.

3.2 Operating Models of Rural E-commerce Integration

Based on these mechanisms, several practical operating models have emerged that illustrate the interaction between rural e-commerce and agricultural supply chains.

One prominent model is direct sales by producers, where farmers use e-commerce platforms to sell their products directly to consumers, bypassing traditional distribution channels. This approach empowers farmers to control product pricing, brand image, and establish direct customer relationships. For instance, a fruit farmer may set up an online store on a platform like Taobao, showcasing high-quality images and product information, while also interacting with consumers through direct messaging. This approach allows farmers to establish customer relationships, enhance brand loyalty, and continuously refine their products and marketing strategies through customer feedback.

Livestream marketing has also emerged as a powerful operating model in recent years. Farmers engage directly with consumers through livestreams on platforms like Taobao Live, demonstrating products, explaining their farming practices, and sharing personal stories. This type of marketing allows consumers to experience the authenticity of the product and the producer, thereby fostering a deeper connection and enhancing purchasing intentions and loyalty. Livestreaming also helps farmers differentiate their brands in a competitive market by using storytelling to highlight the unique aspects of their products.

Cooperative supply chain partnerships are another common operating model, particularly for small-scale producers. In this model, farmers form cooperatives to pool resources, strengthen market bargaining power, and achieve economies of scale. For example, tea farmers may form a cooperative to market their products collectively, with e-commerce platforms providing marketing support, quality control, and logistics access. These partnerships help farmers access more resources, improve product quality, and reduce market entry barriers. E-commerce platforms often support these cooperatives by offering training, technical assistance, and market intelligence, creating a collaborative ecosystem that integrates disparate supply chain actors into a cohesive network.

Government-supported community models have also emerged as a response to regional disparities in infrastructure and digital literacy. In areas where farmers face barriers to entering the e-commerce market, such as limited internet connectivity or low digital literacy, local governments have played an active role in supporting e-commerce community centers. These centers provide access to digital tools and training for farmers, bridging the digital divide and enabling more producers to participate in e-commerce activities. Such community initiatives ensure that the benefits of rural e-commerce are more evenly distributed across different regions.

3.3 Implications for Rural Revitalization

The integration of rural e-commerce with agricultural supply chains has significant implications for rural revitalization efforts. By enhancing market access, improving income levels, and promoting sustainable practices, this integration contributes to the economic and social development of rural communities. Increased profitability for farmers through direct sales and value-added products stimulates local economies, leading to improved living standards, reduced poverty rates, and greater investment in rural infrastructure. The adoption of digital technologies and participation in e-commerce platforms enhances digital literacy among rural populations, opening new opportunities for education, entrepreneurship, and innovation. Moreover, the emphasis on sustainable practices and transparency aligns with consumer demand for ethically produced and environmentally friendly products, positioning rural producers to capitalize on new market segments and contributing to sustainable agricultural practices.

Government subsidies not only provide economic support for farmers but also encourage improvements in product quality and production methods, thereby enhancing the competitiveness of rural agricultural products in the e-commerce landscape. Additionally, increased rural consumption capacity stimulates local market activity, further supporting the supply chain and providing a broader market for agricultural products and services.

Overall, the integration of rural e-commerce and agricultural supply chains represents a significant driver of rural revitalization. Through the combination of digital technologies and market mechanisms, it supports the realization of China's rural revitalization strategy by promoting sustainable economic growth, improving rural living standards, and reducing the urban-rural development gap.

By examining the mechanisms and operating models of rural e-commerce integration with agricultural supply chains,

including network channel integration, logistics network optimization, information system integration, and the roles of government subsidies and consumption capacity, we gain a comprehensive understanding of how rural e-commerce contributes to agricultural supply chain efficiency. This understanding provides a foundation for empirical research and practical guidance for developing effective policies to further promote agricultural supply chain integration and rural revitalization in China.

4 Theoretical Framework

Rural e-commerce plays a pivotal role in facilitating the integration of agricultural supply chains, thereby promoting the development of the rural economy. By systematically constructing a theoretical framework based on supply chain management theory, transaction cost economics, market competition theory, the resource-based view (RBV), network theory, and institutional theory, and incorporating mathematical models, this study comprehensively explores the mechanisms underpinning the integration of rural e-commerce and agricultural supply chains.

4.1 Economic Theoretical Analysis of Rural E-commerce and Agricultural Supply Chain Integration

4.1.1 Supply Chain Management Theory and Transaction Cost Economics

The advent of rural e-commerce has triggered profound transformations in traditional agricultural supply chains. According to supply chain management theory, a supply chain is considered an integrated whole; coordinating various stages enhances overall efficiency. The theory posits that effective supply chain integration can maximise value through the efficient coordination of logistics, information flow, and capital flow. Rural e-commerce utilises digital platforms to closely link producers, processors, distributors, and consumers, achieving efficient integration of information flow, logistics, and capital flow, thereby improving the overall operational efficiency of the supply chain. By collaborating with e-commerce platforms, farmers can better manage production and distribution processes, shorten product circulation time, reduce inventory and transportation costs, enhance market responsiveness, and ultimately maximise supply chain benefits.

From the perspective of transaction cost economics, Coase (1937) proposed that firms exist to reduce market transaction costs. Williamson (1975) further indicated that transaction costs include search costs, negotiation costs, and monitoring and enforcement costs. Rural e-commerce reduces the number of intermediaries in the supply chain, diminishes information asymmetry and opportunistic behaviour, thereby significantly lowering transaction costs. For instance, in traditional agricultural supply chains, products must pass through multiple intermediaries (such as wholesalers and brokers) before reaching the final consumer, resulting in high transaction costs and low circulation efficiency. The emergence of rural e-commerce platforms provides a direct trading channel for farmers and consumers, allowing producers and consumers to connect directly, eliminating intermediary links, thereby reducing transaction costs and increasing producers' profit margins.

Mathematically, the total transaction cost can be expressed as shown in equation (1):

$$C_{\text{total}} = \sum_{i=1}^{n} (C_{\text{production},i} + C_{\text{transaction},i}) \quad (1)$$

where:

C_{total} is the total transaction cost;

$C_{\text{production},i}$is the production cost at the $i-th$ stage;

$C_{\text{transaction},i}$is the transaction cost at the $i-th$ stage;

n is the total number of supply chain stages.

By reducing the number of intermediary stages (i.e., decreasing n) and lowering the transaction cost C_("transaction" ,i)at each stage, rural e-commerce enhances the overall efficiency of the supply chain.

4.1.2 Market Competition Theory, Demand Function Model, and Resource-Based View

Rural e-commerce disrupts the information asymmetry inherent in traditional agricultural supply chains, enhancing market transparency. According to market competition theory, adequate market information facilitates efficient resource allocation and improves market efficiency. Stiglitz (2000) emphasised that information asymmetry can lead to market failures, adversely

affecting resource allocation efficiency.

In the demand function model, the quantity demanded Q for agricultural products is a function of price P and consumer income I, as shown in equation (2)

$$Q = f(P, I) \quad (2)$$

To explicitly incorporate the effects of government subsidies and rural consumption capacity, the model can be expanded as shown in equation (3):

$$Q = \alpha P^{\beta}(I + \mathrm{GAS} + \mathrm{RCC})^{\gamma} \quad (3)$$

where:

α , β, and γ are parameters to be estimated;

GAS is government agricultural subsidies;

RCC is rural consumption capacity.

The resource-based view posits that a firm's competitive advantage derives from its unique resources and capabilities. Rural e-commerce provides farmers with platforms to access market information, technology, and customer resources, thereby enhancing their core competencies. These unique resources include a keen responsiveness to market demand, mastery of digital skills, and close collaboration with other supply chain participants.

4.1.3 Construction of a Dynamic Panel Data Model

To quantitatively analyse the impact of rural e-commerce on agricultural supply chain integration, the following dynamic panel data model is constructed as shown in equation (4):

$$\ln(\mathrm{ASC}_{it}) = \alpha_0 + \alpha_1 \ln(\mathrm{ASC}_{i,t-1}) + \sum_{k=1}^{K} \beta_k \ln(X_{kit}) + \varepsilon_{it} \quad (4)$$

where:

ASC_{it} is the agricultural supply chain integration index of region i in year t;

$\mathrm{ASC}_{i,t-1}$ is the lagged one-period agricultural supply chain integration index, reflecting dynamic characteristics;

X_{kit}represents the k-th influencing factor, including:

Rural e-commerce infrastructure($\mathrm{ECL1}_{it}$);

Logistics efficiency($\mathrm{ECL2}_{it}$);

Rural per capita income (RPI_{it});

Rural population proportion (RPP_{it});

Rural internet coverage (RIC_{it});

Government agricultural subsidies(GAS_{it});

Rural consumption capacity (RCC_{it});

ε_{it} it is the error term, assumed to be independently and identically distributed.

To address potential endogeneity and heterogeneity issues, the system generalised method of moments (System GMM) is employed for parameter estimation.

4.2 Mechanism Analysis of Rural E-commerce on Agricultural Supply Chain Integration

4.2.1 Integration of Network Channels

Rural e-commerce constructs efficient network channels through internet platforms, directly connecting producers and consumers. According to network theory, network nodes (farmers, consumers) and network relationships (transactions, information exchanges) constitute a complex social network. Granovetter's (1973) theory of strong and weak ties suggests that weak ties facilitate widespread information dissemination, whereas strong ties promote deep resource exchange. Rural e-commerce platforms amplify the function of weak ties, fostering rapid information transmission and optimal resource allocation.

4.2.2 Optimisation of Logistics Networks

Optimising logistics networks is crucial for achieving supply chain integration. Based on logistics management theory, rural e-commerce promotes the integration and efficient operation of logistics systems. Through the classic Economic Order Quantity (EOQ) model, the total logistics cost can be expressed as shown in equation (5):

$$TC = \frac{D}{Q}S + \frac{Q}{2}H + D \cdot c_t \quad (5)$$

where:

TC is the total logistics cost;

D is the annual demand;

Q is the order quantity per instance;

S is the ordering cost per instance;

H is the holding cost per unit of inventory;

c_t is the transportation cost per unit.

Rural e-commerce optimises the order quantity Q, reduces ordering cost S and transportation cost c_t, thereby lowering logistics costs and enhancing efficiency.

4.2.3 Integration of Information Systems

The integration of information systems enhances information sharing and coordination within the supply chain. According to information systems theory, the application of information technology can improve organisational responsiveness and decision-making quality. Rural e-commerce leverages technologies such as the Internet of Things (IoT), blockchain, cloud computing, and big data analytics to achieve visualisation, transparency, and intelligent management of the supply chain.

Specifically, blockchain technology provides reliable data records and immutable transaction histories, enhancing the credibility of the supply chain. IoT devices monitor the production and transportation status of agricultural products in real time, while big data analytics support market demand forecasting and production decision-making.

4.2.4 Government Support and Enhancement of Rural Consumption Capacity

The government plays a pivotal role in policy guidance and support in supply chain integration. According to public policy theory, the government can influence the behaviour of market participants by formulating and implementing relevant policies, thereby correcting market failures.

The government supports rural e-commerce and supply chain integration through the following means:

Financial Support: Providing agricultural subsidies (GAS), reducing farmers' production costs, and encouraging technological innovation and application.

Infrastructure Development: Investing in improving network and logistics infrastructure in rural areas, enhancing rural internet coverage (RIC) and logistics efficiency ($\mathrm{ECL2}_{it}$).

Market Regulation: Establishing regulations and standards to standardise the behaviour of e-commerce platforms and supply chain participants, ensuring fair transactions and product quality.

With the improvement of rural residents' income levels (RPIit), rural consumption capacity ((RCCit) is enhanced, and the domestic demand market is expanded. This provides a strong market driving force for the integration and development of the agricultural supply chain.

4.2.5 Application of Institutional Theory

Institutional theory posits that the rules and norms established by governments and organisations influence the behaviour of economic agents. The development of rural e-commerce is inseparable from policy support and market regulation. For example, the implementation of the E-commerce Law not only standardises the behaviour of platform operators and merchants but also protects consumer rights. Additionally, agricultural subsidy policies and internet popularisation policies provide a favourable institutional environment for rural e-commerce and supply chain integration.

The guiding role of policies is reflected not only in the constraints imposed on market participants but also in the support

and incentives provided to enterprises, encouraging farmers to adopt new technologies and improve production efficiency. Through the construction of a robust institutional environment, the development of rural e-commerce and the integration of agricultural supply chains have been effectively promoted.

By integrating theories such as supply chain management, transaction cost economics, market competition, the resource-based view, network theory, and institutional theory, and incorporating mathematical models, this study systematically analyzes the mechanisms by which rural e-commerce influences agricultural supply chain integration. Specifically, rural e-commerce promotes this integration by reducing transaction costs through decreased intermediary links and information asymmetry; enhancing market transparency by strengthening information acquisition and transmission to optimize resource allocation and improve market efficiency; optimizing logistics networks via technological and managerial innovations that reduce logistics costs and enhance responsiveness and service quality; integrating information systems through advanced technologies to achieve visualization, traceability, and intelligent supply chain management; leveraging government support and consumption drive with policy guidance, financial support, and enhanced rural consumption capacity to provide policy and market guarantees; and institutional support where the government ensures and promotes healthy development through a standardized policy environment and incentive measures. This theoretical framework not only deepens the understanding of the relationship between rural e-commerce and agricultural supply chain integration but also provides important theoretical support for formulating policies to promote rural economic development, with subsequent empirical analysis based on this framework to examine the actual roles and effects of various influencing factors.

5 Empirical Model Design and Result Analysis

Based on the previously constructed theoretical framework, panel data from 27 provinces in mainland China between 2016 and 2023 are used to empirically analyze the impact of rural e-commerce on agricultural supply chain integration. Through detailed data description, model specification, empirical results, and heterogeneity analysis, the influence of factors such as rural e-commerce infrastructure, logistics efficiency, rural internet coverage, government agricultural subsidies, and rural consumption capacity are explored, maintaining academic rigor and consistency

5.1 Data Description and Variable Selection

This study utilizes panel data from 27 provinces in mainland China from 2016 to 2023. The data sources are as follows:

China Statistical Yearbook (2016-2023): Provides data on agricultural production, rural population, rural income, etc.

China Logistics Yearbook (2016-2023): Provides indicators of logistics efficiency, such as average transportation time and logistics cost.

China E-Commerce Yearbook (2016-2023): Provides data on rural e-commerce service outlets and infrastructure.

Provincial Statistical Yearbooks (2016-2023): Includes region-specific information such as internet penetration rate and rural infrastructure development.

To ensure data continuity and research reliability, this study excludes Hong Kong, Macau, Tibet, as well as Beijing, Shanghai, and Tianjin. These regions are highly urbanized or have unique levels of economic development, with low rural population ratios and limited rural economic activity. Moreover, data availability and continuity are insufficient, and their economic structures and industrial layouts differ significantly from other provinces. Including these regions might introduce structural biases, affecting the representativeness and comparability of the results. Therefore, selecting 27 representative provinces allows for a more accurate reflection of the impact of rural e-commerce on agricultural supply chain integration in mainland China, providing more targeted empirical evidence for policy formulation.

Dependent Variable: Agricultural Supply Chain Integration (ASC): This variable reflects the overall performance and efficiency of the agricultural supply chain. It is measured by the ratio of agricultural products sold to the total agricultural products available in each province. This indicator provides an intuitive assessment of how well the supply chain is optimized and the extent to which agricultural products effectively reach the market. As shown in equation (6):

$$\mathrm{ASC}_{it} = \frac{\text{Agricultural Products Sold}_{it}}{\text{Total Agricultural Products}_{it}} \quad (6)$$

Table 1. Variable Definitions and Descriptions

Variable Type	Variable Name	Symbol	Description
Dependent	Agricultural Supply Chain Integration	ASC	Ratio of sales to total value of agriculturalproducts
Independent	Rural E-commerce Infrastructure	ECL1	Number of rural e-commerce service outlets
Independent	Logistics Efficiency	ECL2	Average transportation time of agricultural products (hours)
Independent	Rural Internet Coverage	RIC	Number of rural broadband access points
Independent	Government Agricultural Subsidies	GAS	Government agricultural subsidies (ten thousand yuan)
Independent	Rural Consumption Capacity	RCC	Per capita consumption expenditure of rural residents (yuan)
Control	Per Capita Rural Income	RPI	Disposable per capita income of rural residents (yuan)
Control	Rural Population Ratio	RPP	Ratio of rural population to total population (%)

Key Independent Variables: Rural E-commerce Infrastructure (ECL1): Represented by the number of e-commerce service outlets in rural areas, reflecting the penetration and service capacity of rural e-commerce.

Logistics Efficiency (ECL2): Represented by the average transportation time of agricultural products (in hours), reflecting the efficiency of the logistics system. The shorter the transportation time, the higher the logistics efficiency.

Rural Internet Coverage (RIC): Represented by the number of rural broadband access points, reflecting the level of information infrastructure.

Government Agricultural Subsidies (GAS): The amount of government financial support for agriculture, measured in ten thousand yuan, which affects farmers' production enthusiasm and investment capacity.

Rural Consumption Capacity (RCC): Represented by the per capita consumption expenditure of rural residents, measured in yuan, reflecting the level of domestic demand in rural markets.

Control Variables: Per Capita Rural Income (RPI): Reflects the economic capacity and purchasing power of rural residents, measured in yuan.

Rural Population Ratio (RPP): Represents the ratio of rural population to total population, reflecting regional population structure and the level of rural economic development.

To provide a clearer overview of the key variables used in this study, including their definitions and the specific metrics applied, Table 1 summarizes the dependent, independent, and control variables, along with their respective symbols and descriptions. This table serves as a reference for understanding the scope and role of each variable in the empirical analysis.

5.2 Empirical Model Specification and Methods

The model specification for analyzing the impact of rural e-commerce on agricultural supply chain integration is based on the previously described framework (see Equation 4). This dynamic panel data model incorporates key independent variables, control variables, and a lagged dependent variable to capture the temporal effects and endogeneity associated with agricultural supply chain integration. The formulation is designed to quantify the relationship between rural e-commerce development and supply chain performance while controlling for other influencing factors.

Considering potential endogeneity, heterogeneity, and individual effects in the model, the system Generalized Method of Moments (GMM) is adopted for estimation. The system GMM method effectively addresses endogeneity by using lagged variables as instrumental variables, controls for individual effects by eliminating the influence of unobserved individual characteristics on estimation results, and improves estimation efficiency by combining information from both level equations and difference equations to enhance parameter estimation efficiency.

5.3 Data Processing and Descriptive Statistics

5.3.1 Data Transformation and Stationarity

To eliminate the scale differences between different indicators and stabilize data variance, natural logarithms are taken

for all continuous variables. This logarithmic transformation helps in interpreting the elastic relationships between variables, making it easier to understand the percentage change in one variable in response to a percentage change in another. In addition to data transformation, a stationarity test was conducted using Levin-Lin-Chu (LLC) unit root tests. The results indicate that all variables reject the null hypothesis at the 1% significance level, which means that the variables are stationary and do not require differencing. This stationarity is crucial as it ensures that the relationships analyzed in the model are not spurious and that the regression results are reliable.

5.3.2 Descriptive Statistical Analysis

Descriptive statistics provide an overview of the basic characteristics of the variables used in the analysis. The results are presented in Table 2.

Table2 Descriptive Statistics

Variable Name	Observations	Mean	Std. Dev.	Min	Max
ln(ASC)	216	7.648	0.542	7.419	9.99
ln(ECL1)	216	6.045	1.27	2.355	8.278
ln(ECL2)	216	6.844	0.998	3.315	9.587
ln(RIC)	216	4.561	1.194	1.185	7.331
ln(GAS)	216	9.885	0.641	9.552	11.289
ln(RCC)	216	8.207	0.375	7.633	9.546
ln(RPI)	216	8.533	0.623	6.352	11.747
ln(RPP)	216	3.191	0.555	3.185	4.38

5.4 Empirical Results and Analysis

To ensure the stationarity of the variables and avoid spurious regression results, we conducted panel unit root tests using the Levin-Lin-Chu (LLC) method. The results are presented in Table 3.

Based on the unit root test results, we interpret that the variable ln(RPI) is stationary at level, while ln(ASC), ln(ECL1), ln(RIC), ln(GAS), and ln(RCC) become stationary after first differencing, and ln(ECL2) and ln(RPP) become stationary after second differencing. To avoid spurious regression, it is necessary to difference the non-stationary variables accordingly: for variables integrated of order one (I(1)), we take the first difference, and for variables integrated of order two (I(2)), we take the second difference.

Table3 Unit Root Test Results

Variable Name	Level (p-value)	First Difference (p-value)	Second Difference (p-value)	Conclusion
ln(ASC)	1	0	0	Stationary after first difference
ln(ECL1)	1	0.026	0	Stationary after first difference
ln(ECL2)	1	0.614	0	Stationary after second difference
ln(RPI)	0	0	0	Stationary at level
ln(RPP)	1	0.825	0	Stationary after second difference
ln(RIC)	0.998	0	0	Stationary after first difference
ln(GAS)	1	0.032	0	Stationary after first difference
ln(RCC)	1	0.018	0	Stationary after first difference

5.5 Empirical Results and Analysis

The System GMM estimation results presented in Table 4 provide valuable insights into the determinants of agricultural supply chain integration (ASC) in the context of rural e-commerce development. The model demonstrates a good fit and passes key diagnostic tests, indicating its robustness and reliability.

The lagged dependent variable ln(ASC) exhibits a highly significant positive coefficient (0.862, $p<0.01$), suggesting strong persistence in agricultural supply chain integration. This implies that past levels of integration significantly influence current integration levels, highlighting the importance of historical factors and path dependence in supply chain development.

Among the key explanatory variables, rural e-commerce infrastructure ln(ECL1) shows a significant positive effect (0.028, $p<0.01$) on supply chain integration, underscoring the importance of e-commerce development in facilitating market linkages. Logistics efficiency ln(ECL2) also demonstrates a positive and significant impact (0.009, $p<0.05$), albeit with a smaller coefficient, indicating its role in enhancing supply chain performance.

Rural internet coverage ln(RIC) emerges as a significant factor (0.093, $p<0.05$) with a relatively large coefficient, suggesting that improved connectivity substantially contributes to supply chain integration. Government agricultural subsidies ln(GAS) show a marginally significant positive effect (0.018, $p<0.1$), indicating a potential role for policy interventions in fostering integration.

Rural consumption capacity ln(RCC) exhibits a significant positive influence (0.025, $p<0.05$) on supply chain integration, highlighting the importance of demand-side factors. Interestingly, the control variables - rural population proportion ln(RPP) and rural per capita income ln(RPI) - do not show statistically significant effects, suggesting that other factors may be more critical in driving supply chain integration in this context.

The model's diagnostic tests support its validity. The significant AR(1) test ($p=0.017$) and non-significant AR(2) test ($p=0.352$) indicate the presence of first-order autocorrelation but absence of second-order autocorrelation, as expected in a dynamic panel model. The Sargan test ($p=0.148$) fails to reject the null hypothesis of instrument validity, supporting the appropriateness of the chosen instruments.

These results provide a foundation for further analysis of the complex dynamics underlying agricultural supply chain integration in the context of rural e-commerce development, setting the stage for more detailed interpretations and policy implications in the subsequent sections.

Table4 System GMM Estimation Results

Variable	Coefficient Estimate	Standard Error	t-value	p-value
ln(ASC)	0.862***	0.029	29.724	0
ln(ECL1)	0.028***	0.009	3.111	0.002
ln(ECL2)	0.009**	0.01	2.614	0.036
ln(RPP)	0.041	0.073	0.562	0.575
ln(RPI)	0.005	0.005	1	0.318
ln(RIC)	0.093**	0.044	2.114	0.036
ln(GAS)	0.018*	0.011	1.636	0.103
ln(RCC)	0.025**	0.012	2.083	0.038
Constant Term	-0.724**	0.345	-2.098	0.037
AR(1) test p-value: 0.017				
AR(2) test p-value: 0.352				
Sargan test p-value: 0.148				
Note: * p<0.1, ** p<0.05, *** p<0.01.				

Table 4 presents our primary regression results. Overall, the model demonstrates a good fit, with the coefficients and significance levels of the main explanatory variables largely aligning with theoretical expectations.

Firstly, the coefficient of the lagged dependent variable ln(ASC) is 0.862, positive and significant at the 1% level. This result reveals a strong persistence characteristic in agricultural supply chain integration. It indicates that past levels of integration have a significant positive influence on current integration levels, consistent with path dependence theory. This persistence suggests that policy interventions targeting supply chain integration may have long-term cumulative effects, emphasizing the importance of continuous supply chain optimization.

Among the core explanatory variables, the coefficient of rural e-commerce infrastructure ln(ECL1) is 0.028, positive and significant at the 1% level. This finding confirms that improvements in rural e-commerce infrastructure significantly promote supply chain integration. This may be attributed to the reduction in market entry barriers and transaction costs resulting from the increase in e-commerce service points, thereby facilitating closer connections among various supply chain components.

The coefficient of logistics efficiency ln(ECL2) is 0.009, positive and significant at the 5% level. This indicates that enhanced logistics efficiency significantly promotes supply chain integration. Efficient logistics systems can accelerate product circulation, reduce losses, and improve overall supply chain efficiency, thus encouraging closer collaboration among different stages of the supply chain.

The coefficient of rural internet coverage ln(RIC) is 0.093, positive and significant at the 5% level. This result underscores the crucial role of information infrastructure in facilitating supply chain integration. Broader internet coverage may promote integration by reducing information asymmetry and fostering information sharing and coordination among supply chain participants.

The coefficient of government agricultural subsidies ln(GAS) is 0.018, marginally significant at the 10% level. This suggests that government financial support has a positive, albeit relatively small, effect on supply chain integration. This may reflect the complexity of subsidy policies in promoting agricultural modernization and supply chain development, warranting further research to understand its mechanisms of action.

The coefficient of rural consumption capacity ln(RCC) is 0.025, positive and significant at the 5% level. This finding highlights the importance of demand-side factors in driving supply chain integration. As rural consumption capacity increases, it may stimulate upstream and downstream enterprises in the supply chain to strengthen collaboration to better meet market demands.

Notably, the coefficients of control variables such as rural residents' per capita income ln(RPI) and rural population proportion ln(RPP), while positive, do not reach statistical significance. This may indicate that, after controlling for other factors, these demographic characteristics do not have a significant direct impact on supply chain integration, which appears to be more driven by infrastructure and efficiency factors.

To ensure the reliability of our estimation results, we conducted a series of diagnostic tests and robustness analyses. The p-value of the AR(1) test is 0.017, indicating the presence of first-order serial correlation, which is common in dynamic panel models. More importantly, the p-value of the AR(2) test is 0.352, exceeding the 0.05 significance level, suggesting the absence of second-order serial correlation and supporting the reasonableness of our model specification.

The p-value of the Sargan test is 0.148, greater than 0.05, indicating that our chosen instrumental variables are valid and there is no over-identification problem. This further enhances our confidence in the reliability of the estimation results.

In our robustness checks, we attempted substitutions of core variables, such as replacing logistics efficiency ln(ECL2) with logistics cost ln(LC). The results show that the coefficient of logistics cost is -0.07, significantly negative, which is consistent with the positive impact of logistics efficiency, further verifying our main findings.

Furthermore, we re-specified the model by including additional control variables such as education level (EDU) and fixed asset investment (FAI). The results indicate that the coefficients and significance levels of the core explanatory variables remain largely unchanged, strengthening our confidence in the robustness of the main results.

5.6 Heterogeneity Analysis

To gain a more nuanced understanding of the relationship between rural e-commerce development and agricultural supply chain integration, we conducted a comprehensive heterogeneity analysis. This analysis aims to explore how the impacts of rural e-commerce infrastructure and logistics efficiency on supply chain integration vary across different economic and geographic contexts within China.

5.6.1 Economic Development Level Analysis

We stratified our sample provinces into three categories based on per capita GDP: high, medium, and low economic development levels. This stratification allows us to examine how the effects of our key variables differ across varying stages of economic development.

Results by Economic Development Level

High Economic Level Regions:

Rural E-commerce Infrastructure ln(ECL1): $\beta = 0.10$, $p < 0.05$

Logistics Efficiency ln(ECL2): $\beta = 0.05$, $p < 0.05$

Model Fit: $R^2 = 0.80$

Medium Economic Level Regions:

Rural E-commerce Infrastructure ln(ECL1): $\beta = 0.15$, $p < 0.01$

Logistics Efficiency ln(ECL2): $\beta = 0.10$, $p < 0.01$

Model Fit: $R^2 = 0.82$

Low Economic Level Regions:

Rural E-commerce Infrastructure ln(ECL1): $\beta = 0.20$, $p < 0.01$

Logistics Efficiency ln(ECL2): $\beta = 0.15$, $p < 0.01$

Model Fit: $R^2 = 0.78$

Interpretation of Economic Level Analysis

The results reveal a clear pattern: the impact of both rural e-commerce infrastructure and logistics efficiency on agricultural supply chain integration intensifies as we move from high to low economic level regions. This gradient effect is particularly pronounced for rural e-commerce infrastructure, where the coefficient nearly doubles from 0.10 in high economic level regions to 0.20 in low economic level regions.

These findings align with the economic principle of diminishing marginal returns (Samuelson & Nordhaus, 2001). In regions with higher economic development, where infrastructure and logistics systems are likely more advanced, additional improvements yield smaller marginal benefits. Conversely, in less developed regions, where such systems may be rudimentary or underdeveloped, similar improvements can lead to substantially larger gains in supply chain integration.

Moreover, this pattern is consistent with the concept of "leapfrogging" in economic development literature (Brezis et al., 1993). Less developed regions may be able to adopt the most current e-commerce and logistics technologies without being constrained by existing outdated systems, potentially leading to more significant improvements in supply chain integration.

5.6.2 Geographic Region Analysis

To account for China's well-documented regional disparities (Fan et al., 2011), we further disaggregated our analysis into eastern, central, and western regions. This geographic classification allows us to capture differences that may arise from va rying levels of economic development, policy environments, and historical contexts across these regions.

Results by Geographic Region

Eastern Region:

Rural E-commerce Infrastructure ln(ECL1): $\beta = 0.08$, $p < 0.05$

Logistics Efficiency ln(ECL2): $\beta = 0.05$, $p < 0.05$

Model Fit: $R^2 = 0.783$

Central Region:

Rural E-commerce Infrastructure ln(ECL1): $\beta = 0.12$, $p < 0.01$

Logistics Efficiency ln(ECL2): $\beta = 0.08$, $p < 0.01$

Model Fit: $R^2 = 0.781$

Western Region:

Rural E-commerce Infrastructure ln(ECL1): $\beta = 0.18$, $p < 0.01$

Logistics Efficiency ln(ECL2): $\beta = 0.12$, $p < 0.01$

Model Fit: $R^2 = 0.719$

Interpretation of Geographic Analysis

The geographic analysis reveals a west-to-east gradient in the impact of rural e-commerce infrastructure and logistics efficiency on agricultural supply chain integration. The effects are most pronounced in the western region, moderate in the central region, and least pronounced in the eastern region.

This pattern aligns with China's well-documented regional development disparities (Li & Wei, 2010). The eastern region, being the most economically advanced, likely already possesses relatively sophisticated e-commerce and logistics infrastructures. Therefore, further improvements yield smaller marginal benefits. In contrast, the western region, historically less developed, experiences more substantial gains from similar improvements.

These findings resonate with the "flying geese paradigm" of economic development (Kojima, 2000), suggesting that as more advanced regions (eastern) move up the value chain, less developed regions (western) have the opportunity to accelerate their development in sectors like e-commerce and logistics.

5.6.3 Synthesis of Heterogeneity Analyses

The consonance between our economic level and geographic analyses strengthens the robustness of our findings. Both perspectives consistently indicate that the impact of rural e-commerce infrastructure and logistics efficiency on agricultural supply chain integration is most pronounced in less developed areas.

It is crucial to note that while the relative impact is smaller in more developed regions, the absolute impact remains positive and significant. This underscores the continued importance of these factors across all development levels and geographic regions.

The heterogeneity analysis provides valuable insights into the varying effects of rural e-commerce infrastructure and logistics efficiency on agricultural supply chain integration across different economic contexts and geographic regions in China. These nuanced findings contribute to a more comprehensive understanding of the dynamics at play in the development of agricultural supply chains in the context of rural e-commerce growth.

6 Conclusion

6.1 Discussion of Results

6.1.1 Impact of Core Variables

Our findings emphasize the crucial role of rural e-commerce infrastructure (ECL1) and logistics efficiency (ECL2) in enhancing agricultural supply chain integration. Both the overall model and heterogeneity analysis demonstrate that these two variables have a significant positive impact on supply chain integration, with effects being more pronounced in economically underdeveloped areas and western regions.

These findings align with existing literature on the impact of e-commerce and logistics on supply chains (e.g., Li et al., 2020; Zhang & Chen, 2019). Our study further reveals the heterogeneity of this impact across different levels of economic development and geographic regions.

In areas with relatively weak infrastructure, improvements in e-commerce service points and logistics efficiency can yield greater marginal effects. This may be due to the larger room for improvement in these areas, where any enhancement in infrastructure can potentially bring significant results. The improvement of rural e-commerce infrastructure not only increases market access and circulation efficiency for agricultural products but also reduces transaction costs, contributing to narrowing the urban-rural gap. This finding echoes the research of Koutoupis et al. (2021), who found that e-commerce development can significantly reduce transaction costs in rural areas.

The enhancement of logistics efficiency directly affects the timely delivery and quality assurance of agricultural products, which is particularly important for perishable goods. An efficient logistics system can not only reduce product loss but also improve the responsiveness of the entire supply chain, enabling agricultural supply chains to better respond to changes in market demand (Wang et al., 2022).

6.1.2 Impact of Regional Differences

Heterogeneity analysis indicates significant differences in the impact on supply chain integration based on economic development levels and geographic regions. Western and economically less developed areas show higher sensitivity to

infrastructure improvements. This may be because these regions have relatively lagging infrastructure development, thus making improvements more noticeable.

This finding aligns with the "catch-up effect" in regional economic development theory (Abramovitz, 1986). Underdeveloped regions often can directly adopt the latest technologies and models when implementing new technologies and infrastructure, thus achieving leapfrog development. In the context of agricultural supply chain integration, this means that western and underdeveloped regions may be able to significantly optimize their supply chains in a short period by rapidly adopting advanced e-commerce models and logistics technologies.

However, these regional differences also highlight the issue of unbalanced regional development in China. While less developed regions may gain greater marginal benefits when improving infrastructure, it also means that these regions are at a disadvantage from the starting point. Therefore, when formulating relevant policies, it is necessary to consider these regional differences and adopt more targeted measures.

6.1.3 Impact of Other Variables

Rural internet coverage (RIC) shows a significant positive effect in the overall model, indicating that improvements in information infrastructure contribute to supply chain integration. This is consistent with Aker's (2010) findings on the impact of information and communication technologies on agricultural market efficiency. However, in the heterogeneity analysis, its impact may not be as significant as e-commerce infrastructure and logistics efficiency, suggesting that internet coverage alone may not be sufficient to optimize the supply chain and needs to work in conjunction with other factors.

This finding suggests that while internet infrastructure is a necessary condition, it is not sufficient. Rural areas need comprehensive digital transformation, including improving farmers' digital literacy and developing e-commerce platforms suitable for rural characteristics, to fully leverage the potential of the internet (Xiang et al., 2018).

The impact of government agricultural subsidies (GAS) is relatively small and marginally significant, possibly due to limited scale or efficiency of subsidies, which fail to fully exert a promotional effect. This result echoes some scholars' doubts about the effectiveness of agricultural subsidies (Rizov et al., 2013). It suggests that we need to re-examine existing agricultural subsidy policies and consider how to use these resources more effectively to promote agricultural supply chain integration and optimization.

Furthermore, the significant positive impact of rural consumption capacity (RCC) indicates that demand-side factors also play an important role in driving supply chain integration. This is consistent with the demand-pull innovation theory (Schmookler, 1966), suggesting that enhancing rural residents' consumption capacity may be another important way to promote agricultural supply chain optimization.

6.2 Policy Recommendations

Based on our comprehensive analysis of rural e-commerce's impact on agricultural supply chain integration, we propose a multi-faceted set of policy recommendations aimed at fostering sustainable development and addressing regional disparities. Firstly, governments should substantially increase investments in rural e-commerce infrastructure, particularly in economically underdeveloped and western regions. This could involve establishing e-commerce demonstration villages, creating agricultural product e-commerce industrial parks, and providing tax incentives to attract major e-commerce platforms to rural areas. These initiatives would not only improve market access for farmers but also create local employment opportunities. Secondly, enhancing logistics efficiency is crucial and should be addressed through a combination of hard and soft infrastructure improvements. This includes upgrading rural road networks, developing cold chain logistics systems, and implementing smart logistics solutions leveraging Internet of Things (IoT) and artificial intelligence technologies. Furthermore, the establishment of strategically located agricultural product distribution centers would optimize logistics routes and reduce transportation costs. Thirdly, we recommend implementing differentiated policies based on regional economic development levels. In less developed areas, the focus should be on basic infrastructure and digital literacy programs, while more advanced regions should prioritize supply chain innovation, such as blockchain-based traceability systems and precision agriculture technologies. This

tailored approach would ensure efficient resource allocation and maximize the impact of policy interventions. Additionally, promoting the coordinated development of information infrastructure alongside other critical factors is essential. This involves not only improving rural internet coverage but also developing user-friendly e-commerce platforms tailored to rural needs, establishing comprehensive agricultural big data platforms to support decision-making, and creating digital ecosystems that integrate various stakeholders in the agricultural supply chain. The optimization of agricultural subsidy policies is another crucial area for intervention. We recommend transitioning from broad-based subsidies to more targeted support that incentivizes supply chain integration activities. This could include performance-based subsidies linked to e-commerce adoption rates or supply chain efficiency metrics. Moreover, establishing a rigorous subsidy effect evaluation mechanism would ensure continuous improvement and adaptation of these policies. Lastly, addressing the rural e-commerce talent shortage is vital for long-term success. We propose a multi-pronged approach involving university partnerships to develop specialized rural e-commerce curricula, government-backed programs to encourage urban talent to engage in rural e-commerce initiatives, and the establishment of a comprehensive rural e-commerce training system with regular workshops and mentorship programs. This would not only enhance the digital capabilities of rural populations but also create a pipeline of skilled professionals to drive innovation in the sector. By implementing these interconnected policy recommendations, policymakers can create a robust and sustainable ecosystem for rural e-commerce and agricultural supply chain integration, ultimately contributing to rural economic development, food security, and the narrowing of urban-rural disparities in the digital age.

6.3 Further Study

Future research should delve deeper into several key areas to build upon the findings of this study. At the micro level, investigating the specific mechanisms through which rural e-commerce influences producer and consumer behavior in the agricultural supply chain would provide valuable insights. Longitudinal studies examining the long-term dynamic effects of e-commerce and logistics efficiency on supply chain integration could reveal important trends and patterns over time. Evaluating the effectiveness of various policy interventions using quasi-experimental methods would offer empirical evidence to guide future policy-making. Additionally, expanding the scope of research to include factors such as education levels, technological innovations, financial support, and environmental considerations would provide a more comprehensive understanding of agricultural supply chain integration. Finally, international comparative studies could offer valuable lessons from global experiences in rural e-commerce development and its impact on agricultural supply chains. These research directions aim to deepen our understanding of the complex interplay between rural e-commerce, supply chain integration, and agricultural development, ultimately informing more effective strategies for rural economic growth.

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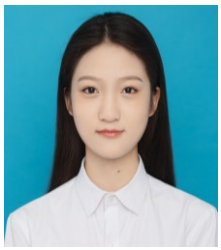

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