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How the digital economy promotes urban–rural integration through optimizing factor allocation: theoretical mechanisms and evidence from China

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The digital economy plays an increasingly crucial role in bridging the gap between urban and rural areas. This study investigates how the development of the digital economy can foster the integrated development of urban and rural areas by optimizing factor allocation, with an emphasis on its potential to narrow the urban-rural divide. The study aims to examine the impact of the digital economy on urban-rural integration, focusing particularly on the mediating role of optimized factor allocation. Using panel data from 30 Chinese provinces between 2011 and 2022, we construct indicators for digital economy development and urban-rural integration. The analysis employs a two-way fixed-effects model, a mediating effect model, and a spatial Durbin model to explore the spatial evolution and impact of the digital economy on urban-rural integration. Findings suggest that the digital economy enhances urban-rural integration both directly and indirectly. It directly contributes to integration and indirectly optimizes the allocation of labor, capital, land, technology, and information, further promoting urban-rural convergence. The effects of these mechanisms exhibit significant threshold effects and spatial heterogeneity. These results underline the importance of accelerating the digital economy and optimizing factor mobility as key strategies for urban-rural integration. Policy implications focus on enhancing the efficiency of resource allocation across urban and rural areas to accelerate balanced development.

KEYWORDS

digital economy, resource allocation, urban–rural integration, mediating effects, spatial spillovers

1 Introduction

Urban–rural disparities are a global problem that provide a serious hindrance to socioeconomic advancement and are closely related to poverty, inequality, economic growth, and sustainable development goals. In some developed nations, rural regions still experience a shortage of resources and slow growth, even though urban areas enjoy higher levels of economic and social services (Turner et al., 2003). This divide is even more pronounced in developing nations, where disparities in resources, infrastructure, and public services are widespread (Geissdoerfer et al., 2017). The differences between urban and rural areas are most evident in economic development, infrastructure, public services, education, and healthcare. These disparities not only limit rural growth but also threaten the stability and cohesion of the nation and the region as a whole. This results in the centralization and uneven allocation of economic assets, further worsening social inequality. The lack of critical resources and economic opportunities in rural areas has resulted in a generally lower quality of life and increased poverty for the inhabitants (Ostrom, 2009). In addition, the gap between rural and urban regions undermines stability and social cohesiveness. The general balance of society can be impacted by social tensions and disagreements that arise from the development gap between urban and rural areas (Purvis et al., 2019). Considerable migration from rural to urban regions has resulted from slow growth in rural areas, placing more demand on urban resources and the environment (Pascual et al., 2023). The inadequate exchange of elements between urban and rural regions is a primary reason for the growing divide between these areas. Rural communities are experiencing a lack of resources and sluggish development as a result of the inadequate flow of resources, cash, talent, and knowledge between urban and rural areas.

Urban–rural cohesion and progress serve as effective strategies for bridging the gap between rural and urban areas and achieving shared prosperity. The rapid expansion of the digital economy introduces both new opportunities and challenges for urban–rural integration. In the context of globalization and swift advancements in information technology, the digital economy has emerged as a key driver of economic and social transformation and advancement. It significantly influences economic growth and industrial reorganization while also facilitating the efficient movement of resources between urban and rural areas through the extensive use of information technology and widespread Internet access. However, while the digital economy presents considerable potential, it also brings forward several challenges that need addressing to ensure a balanced impact on both urban and rural areas.

The positive impacts of the digital economy on urban–rural integration are substantial. Digital technologies improve connectivity, facilitate the efficient allocation of resources, and open new avenues for market integration, especially for rural areas. For example, e-commerce platforms enable rural businesses to reach broader markets, and digital finance enhances access to capital, fostering entrepreneurship in less developed areas. Moreover, the increased use of digital services such as telemedicine and online education helps bridge the service gaps between urban and rural regions, enhancing healthcare and educational access for rural populations (Hou et al., 2023; Zhu et al., 2024; Bian et al., 2025). Nevertheless, the negative impacts should not be overlooked. A key challenge lies in the digital divide, where rural areas, due to limited infrastructure and lower levels of digital literacy, struggle to access the full benefits of the digital economy. This divide exacerbates existing inequalities, leaving some regions at a disadvantage in terms of economic opportunities, social mobility, and quality of life. Furthermore, innovations can sometimes lead to technological displacement, where rural labor forces find it challenging to adapt to new forms of employment in the digital economy, leading to social and economic exclusion (Deng et al., 2023; Zhang Z. et al., 2023; Luo and Zhu, 2024; Tu et al., 2024).

In line with these discussions, the concept of Responsible Research and Innovation (RRI) becomes essential. RRI emphasizes the need for innovation that is not only technologically advanced but also socially responsible, inclusive, and sustainable. Within the framework of RRI, the development of digital technologies should be guided by considerations of ethics, public engagement, and equity. Ensuring that both urban and rural areas can equally benefit from digital advancements requires inclusive policymaking, stakeholder involvement, and measures that mitigate risks such as the digital divide and labor displacement. As such, the principles of RRI urge that the impact of technological innovations be continuously assessed through ethical and societal lenses, ensuring that technological progress fosters equitable growth and does not inadvertently deepen existing disparities (Inigo and Blok, 2019; Jakobsen et al., 2019; Yaghmaei and Van De Poel, 2020; Regan, 2021; Aulianisa, 2024; Kasner et al., 2024).

This plays a crucial role in fostering urban–rural cohesion and development. In recent years, China has achieved notable success in building digital infrastructure, expanding e-commerce, and increasing Internet accessibility. By 2022, China's digital economy was valued at 50.2 trillion yuan, accounting for 41.5% of GDP—equivalent to the contribution of the secondary industry—thereby underscoring the digital economy's prominence as a vital component of the national economy.[1] The latest wave of technological innovation and industrial transformation, powered by advancements in 5G, the Internet of Things, big data, cloud computing, artificial intelligence, and blockchain, has significantly changed how urban and rural communities produce and interact. It is fundamentally reshaping the dynamics and connections between these areas. Leveraging digital technology is crucial for fostering integrated urban–rural development as it enables adaptation to technological advancements, transforms the driving forces of urban–rural growth, and establishes new collaborations between urban and rural residents. The booming Internet economy has opened up new development opportunities for rural areas in China. By vigorously promoting Internet access and information technology, China has significantly accelerated the digital transformation of rural areas, effectively narrowing the digital gap between urban and rural areas. This has not only contributed to a significant improvement in rural infrastructure and public services but also facilitated a more balanced distribution of resources between urban and rural areas and accelerated the pace of urban–rural integration and development. For example, the growth of e-commerce has allowed rural communities better access to markets, expanding sales opportunities for agricultural products and increasing farmers' incomes (Ghobakhloo, 2020). The widespread use of mobile payment systems and the Internet has made financial services more accessible in rural areas, which has aided in the expansion of the rural economy. In addition, the development of digital services such as telemedicine and online education has significantly enhanced healthcare and education in rural regions, reducing the disparity in public services

1 Source: China Academy of Information and Communications Technology, Research Report on the Development of China's Digital Economy (2023).

between urban and rural areas (Pascual et al., 2023). However, a series of challenges have emerged in the process of the digital economy's promotion of urban–rural integrated development, including the widening of the urban–rural digital divide, the unbalanced allocation of resources, and the relative lagging behind of rural digitalization. In view of this, an in-depth investigation of the mechanisms and effects of the digital economy on urban–rural integrated development is not only theoretically important but also of great significance as a guide to practical work.

In this study, we will deeply analyze whether the digital economy exhibits a significant promotion effect on urban–rural integration under the framework of econometrics. If such an effect exists, we further explore what the underlying mechanism of action is. At the same time, we examine whether this effect is characterized by a non-linear threshold, i.e., whether its impact on urban–rural integration changes as the development of the digital economy reaches a certain threshold. In addition, we focus on whether there is variability in this impact across different regional spatial dimensions. To answer these questions comprehensively, this study conducts an empirical study based on the real-world context of the development of the digital economy and urban–rural integration, with a view to providing a valuable marginal contribution to research in this field.

Based on the above background, the choice of China as the region for in-depth research is well justified and diverse: China has made remarkable achievements in the development of the digital economy, especially in the areas of e-commerce, mobile payment, artificial intelligence, and big data, which have demonstrated strong innovative capacity and global influence. This high-level digital economic environment provides an ideal testing ground for researching how digital technologies can promote integrated urban–rural development. The problem of uneven development between urban and rural areas in China is prominent, not only in the distribution of traditional resources but also in the differences in digitalization levels and technology diffusion. Studying China's integrated urban–rural development will help to gain a deeper understanding of this complex phenomenon and provide useful references for other developing countries. The Chinese government has actively promoted the role of the digital economy in urban–rural integration by introducing a series of policy measures to encourage the widespread application of digital technologies in rural areas. This policy-oriented practical exploration provides this study with rich research materials and empirical cases, which help reveal the actual effects of digital economy in different policy environments. China has a vast territory, and the level of economic development and the process of urban–rural integration are characterized by diversity. This geographical difference provides this study with a diversified research perspective, which helps to comprehensively understand the specific impacts of the digital economy in different contexts. China's experience in urban–rural integration and development has important reference value for other countries, especially in other developing countries. By studying the case of China, it can provide these countries with lessons learned and promote the process of global urban–rural integrated development. In summary, China was chosen as the study area not only on the basis of its high level of development of the digital economy but also in view of the complexity of its urban–rural development, the practicality of its policy promotion, the diversity of its geographical characteristics, and the value of international reference.

This research uses data from Chinese provinces between 2011 and 2022 to create an indicator system that can be used to assess the expansion of the digital economy and the integration of urban and rural areas in various geographical areas. The assessment considers both theoretical and practical dimensions. To examine how the digital economy affects urban–rural integration, the study looks at the features of spatial development and makes use of models including the spatial Durbin model, the mediation effect model, and the bidirectional fixed-effects model. This study looks at the mechanisms that underlie the effects of the digital economy on urban–rural integration, with a special emphasis on how effective use of resources such as labor, capital, land, technology, and information may improve integration between urban and rural areas.

This study is organized as follows: section 2 presents an in-depth review of existing literature on the digital economy and urban–rural integration. Section 3 delves into theoretical analysis and formulates research hypotheses. Section 4 describes the research methodology, while section 5 analyzes spatial and temporal patterns. The empirical results are presented in section 6, and section 7 offers policy recommendations as a conclusion.

2 Literature review

2.1 Study on integrated urban–rural development

The concept of integrated urban–rural development has evolved significantly in academic research, focusing on the interrelationship between urban and rural areas. Researchers explore various dimensions of this integration, including economic, social, ecological, spatial, and cultural factors. Urban–rural integration is considered essential for human development as it fosters economic and social links between both areas, improving their mutual benefits.

Conceptual and theoretical frameworks for urban–rural integration, key theories that shape urban–rural integration, include urban–rural linkage theories, Marxist perspectives, and the urban–rural dichotomy in the Lewis–Fei–Ranis model. Moreover, the De Soto model emphasizes coordinated development and complementarity between urban and rural sectors (Lysgård, 2019; Ma et al., 2020). In China, since the 1980s, urban–rural relations have shifted from separation to cooperation and integration, promoted by government policies aimed at facilitating the flow of production factors, resource distribution, and coordinated development between industry and agriculture (Liu et al., 2020).

Current aspects of urban–rural integration, the integration of urban and rural regions, have been evaluated using a variety of indicators. Yang et al. (2021) presented a framework based on the Basis, Drivers, Goals (BDG) approach, analyzing urban–rural integration in China between 2000 and 2018. Their findings indicated a generally low level of integration, with a spatial gradient decline from the southeastern coastal regions to the northwest (Yang et al., 2021). Meanwhile, Ma et al. (2020) developed a comprehensive model for assessing urban–rural quality of life, which also examined spatial patterns and the degree of integration between urban and rural areas (Ma et al., 2020).

As regards the drivers of urban–rural integration, key factors influencing urban–rural integration include market economy dynamics, government interventions, social integration, and the role of the digital economy. The development of the market economy and the digital economy plays a significant role in narrowing the urban–rural divide, although challenges such as uneven development and financial constraints persist, particularly in regions such as Sichuan and Chongqing (Jiang et al., 2024).

2.2 Study on the digital economy

The rapid rise of the digital economy has prompted increased academic attention, particularly with regard to its conceptualization and historical development. The digital economy refers to the integration of technological advancements, particularly in information, communication, and computing technologies, into economic activities.

From the evolutionary aspects of the concept of the digital economy, the term "digital economy" was first introduced in the 1990s by Tapscott, who emphasized its reliance on technological advancements and knowledge networks for driving economic growth (Bowman, 1996). Lane (1999) expanded on this by explaining how the digital economy, powered by the convergence of information, communication, and computing technologies, transformed traditional business models and spurred the growth of e-commerce (Lane, 1999).

China's Digital Economy: China has emerged as a global leader in digital economy development, and scholars have focused on measuring its progress (Tang et al., 2021; Dai et al., 2022; Luo and Zhou, 2022; Minghui et al., 2023; Han et al., 2024). Research by Yang and Li (2021), Liu (2023), and others examined various indicators and methodologies to assess China's digital economy, particularly its regional distribution and growth disparities (Yang and Li, 2021; Liu, 2023). Luo and Zhou, 2022 analyzed the dynamic evolution and geographical inequalities across Chinese provinces, identifying factors that influence regional development (Luo and Zhou, 2022).

Impact on Economic Growth and Social Transformation: The digital economy has significantly boosted economic growth by improving productivity, fostering innovation, and optimizing resource allocation. Studies indicate that it has improved energy efficiency and contributed to industrial transformation, particularly in promoting green technologies and reducing carbon footprints (Wang and Shao, 2023; Tan and Lisi, 2024). Moreover, it has played a pivotal role in advancing the green transformation of industries, especially in China's eastern and central regions (Yang et al., 2024).

2.3 Research on how integrated urban–rural development is affected by the digital economy

As the digital economy continues to expand, its impact on integrated urban–rural development has become a key area of study. The digital economy facilitates the efficient distribution of resources and can bridge the gap between urban and rural areas. Researchers have explored both theoretical and empirical aspects of this dynamic.

Theoretical Insights: The digital economy is theorized to promote the integrated growth of urban and rural areas by improving resource exchange, optimizing production processes, and enhancing social governance. Scholars such as Tang et al. (2021), Zhu and Chen (2022), and others argue that the digital economy can facilitate the integration of urban and rural enterprises by promoting local and external integration in areas such as product supply, income distribution, and social governance (Tang and Gao, 2021; Zhu and Chen, 2022).

Empirical Research: Empirical studies have sought to measure the digital economy's impact on urban–rural integration (Lysgård, 2019; Cheng and Zheng, 2023; Hou et al., 2023; Hu et al., 2023; Le et al., 2023; Man et al., 2023; Zhang, 2023). Yang et al. found that the digital economy positively influences new urbanization by concentrating innovative factors, thereby enhancing the development potential of both urban and rural regions (Yang et al., 2022). Tian and Zhang, 2022 showed how the digital economy has encouraged rural workers to migrate to digital non-farm sectors, promoting skillful labor distribution between urban and rural areas (Tian and Zhang, 2022).

Challenges of the Digital Divide: While the digital economy holds significant promise for bridging the urban–rural divide, challenges remain. One of the most significant barriers is the "digital divide" between urban and rural areas, where rural regions face digital infrastructure gaps, lower technology adoption rates, and lower digital literacy levels. This divide can hinder the integration process as rural populations may struggle to fully benefit from the advancements in the digital economy. Researchers such as He et al. (2020) and Sujarwoto and Tampubolon (2016) highlight how this divide exacerbates inequalities in the distribution of digital resources (Sujarwoto and Tampubolon, 2016; He et al., 2020; Shirazi and Hajli, 2021; Cheng and Zheng, 2023).

2.4 Limitations of existing research

In summary, the relevant research results on the digital economy and urban–rural integration have provided useful references for this study, but there are also deficiencies in the existing research. Most existing research on urban–rural integration and the digital economy focuses on a single dimension, such as digital infrastructure or urban–rural economic integration, overlooking the multidimensional nature of urban–rural integration. In addition, while much of the literature examines the direct effects of the digital economy, its indirect impact on urban–rural integration development through the intermediary mechanism of resource allocation is less frequently discussed. Most studies on the mediating role of factor allocation tend to focus on the impact of the digital economy on a single economic factor, such as capital or labor. However, few studies comprehensively address the systematic impact of the digital economy on the allocation of multiple factors, including labor, capital, land, technology, and information. Furthermore, much of the existing research on the mechanisms through which the digital economy influences urban–rural integration development remains at the theoretical level, with limited empirical verification. In response to the above research gaps, Responsible Research and Innovation (RRI) provides a key framework for understanding how digital innovations can be developed and deployed in a socially responsible and ethical manner. RRI emphasizes that innovations should not be focused solely on economic growth but must also take into account their social, ethical, and environmental impacts (Buonocore et al., 2024). For urban–rural integration, this means ensuring that digital innovations are not only technologically advanced but also inclusive and equitable. The public participation, gender equality, and ethical considerations advocated by RRI can guide the development of policies and strategies to ensure that digital economy initiatives benefit all regions equally, helping to reduce the urban–rural divide. From RRI's perspective, the goal is to ensure that innovation promotes the public good, fosters sustainable development, and benefits both urban and rural populations. Therefore, this study takes 30 provinces in China as research objects, incorporates the digital economy and urban–rural integrated development into a unified analytical framework, makes comprehensive use of econometric models such as the mediated effect model, spatial Durbin model, and threshold model, comprehensively measures the factor allocation in multiple dimensions (labor, capital, land, technology, and information), and systematically analyzes the path mechanism of the digital economy to promote the urban–rural integrated development through optimizing the allocation of factors in an attempt to make up for the lack of empirical verification of this mechanism in existing research.

3 Theoretical analysis and research hypothesis

3.1 The direct impacts of the digital economy on the process of integrating and developing urban and rural areas

Urban–rural integration encompasses the coordinated development of spatial, demographic, economic, social, and ecological dimensions between urban and rural areas. The digital economy plays a critical role in this integration by shaping the spatial relationships between these regions. Research suggests that advancements in the digital economy enhance connectivity through expanded Internet access and improved information infrastructure, which reduces physical distances and increases resource allocation efficiency. For example, in China, the digital economy fosters urban innovation and facilitates spatial clustering, promoting the growth of surrounding cities and supporting urban–rural unification (Huang X. et al., 2022). Moreover, the digital economy has significantly influenced demographic changes by encouraging the movement of populations and reshaping demographic structures through the digitization of local elements. This, in turn, fosters demographic interactions between urban and rural areas (Zhou et al., 2022). Initiatives such as the "digital village" have also played a key role in increasing farmers' income and improving information literacy, thereby promoting the upgrading of rural residents' consumption patterns (Zhang and Ma, 2022). The digital economy also positively impacts the integration of urban and rural economies. Studies indicate that a 1% increase in digital economy development correlates with approximately a 0.4694% improvement in urban–rural integration (Wu et al., 2023). In addition, the growth of digital finance contributes to inclusive urban–rural integration by boosting entrepreneurial activity, particularly for individuals with lower human capital (Hao et al., 2023). Furthermore, the digital economy fosters social interaction and connectivity between urban and rural communities. Digital initiatives, such as the "smart villagers" program, improve residents' quality of life by driving social innovation in rural areas (Zerrer and Sept, 2020). In addition, the digital economy acts as a mediator in urbanization, significantly influencing urbanization processes and boosting the consumption of rural residents (Le et al., 2023). Finally, the integration of urban and rural ecosystems is positively affected by the digital economy. Ecologically, it enhances social governance and the quality of habitats. For example, in the Yellow River Basin, the digital economy stimulates economic vitality and improves ecological conditions by facilitating industrial upgrades and innovation during urban modernization (Qi et al., 2023). The digital economy's relationship with local environmental pollution suggests that it can be used to reduce contamination, although nearby pollution may hinder the growth and development of the digital economy (Xu S. et al., 2022).

This brings us to Hypothesis 1: The digital economy facilitates the integration of urban and rural areas.

3.2 Mediating factor allocation effects of the digital economy on urban–rural integration and development

The digital economy plays a crucial role in bridging the economic gap between urban and rural regions, particularly through the optimal allocation of labor resources. This efficient distribution helps reduce income inequality by enhancing the skills and job prospects of individuals in rural areas, ultimately raising their income levels. Research has shown that digital initiatives, such as online commerce and remote learning, significantly improve rural residents' proficiency and employment opportunities (Magomedov et al., 2020). In addition, the expansion of digital finance has boosted entrepreneurship, especially among individuals with lower human capital, further promoting income equality between urban and rural areas (Hao et al., 2023). By optimizing the allocation of capital, the digital economy helps equalize capital costs between urban and rural locations. The growth of digital finance, particularly its reach into rural areas, has enhanced capital flow efficiency, reduced costs, and promoted a more balanced distribution of capital between these regions (Huang Y. et al., 2023). Furthermore, the digital economy contributes to synchronized development by efficiently managing land resources. Through digital platforms and land management systems, urban and rural areas can coordinate spatial development, optimizing land use. Studies have indicated that digital land management technologies improve land use efficiency and foster better spatial coordination between urban and rural areas (Papaskiri et al., 2019). In addition, big data and virtual platforms provide new opportunities for rural community development, enhancing resource allocation efficiency (Ze, 2019). The digital economy also facilitates the inflow of technological resources into rural regions. By strategically distributing technological elements, it has significantly accelerated the adoption of digital technologies in rural areas. This has helped advance rural modernization, with agricultural e-commerce and remote learning being key drivers of technological infusion (Magomedov et al., 2020). Moreover, digitalization has fostered greater industrial integration in rural areas, promoting the development of high-quality infrastructure and the convergence of primary, secondary, and tertiary industries (Hu et al., 2023). Finally, the digital economy enhances the flow of information and data resources between urban and rural areas. By optimizing the allocation of informational resources, it strengthens connectivity and reduces the information gap between these regions. Studies show that the development of the digital economy facilitates the effective use and allocation of resources by improving the exchange of information between urban and rural areas (Wang et al., 2023). In addition, digital initiatives such as the "Smart Villagers" program have improved information literacy and overall wellbeing among rural residents, contributing to a higher quality of life through information technology (Zerrer and Sept, 2020).

Therefore, Hypothesis 2 is proposed: The digital economy can indirectly promote urban–rural integration by improving the allocation of resources.

3.3 There is a threshold effect that affects how the digital economy affects the integration and growth of urban and rural areas

The digital economy plays a pivotal role in fostering the convergence of urban and rural communities. It not only improves the efficient distribution of resources but also significantly impacts different stages of development. The correlation between the extent of digital economy advancement and the process of integrating urban and rural areas is not linear. Research indicates that in its early stages, the expansion of the digital economy can significantly reduce the wealth gap between urban and rural areas. Initially, the digital economy helps decrease income inequality between these regions, but in the medium and long terms, the gap can widen once more as the digital economy expands (Dai et al., 2022). A "U-shaped "curve indicates that the link between the digital economy and its consequences varies depending on the stage of development. Moreover, the effects of digital money vary geographically. According to the research, digital money influences urban–rural integration more strongly in the eastern area while having a relatively less impact in the middle and western regions (Hao et al., 2023). This demonstrates a threshold effect by showing how the influence of the digital economy varies by location and is limited by disparities in regional development. Furthermore, the widespread use of digital technology has promoted the effective use of land resources in both urban and rural areas. The effectiveness of using land resources has increased with the adoption of digital land management technology; however, its impacts varied greatly depending on the level of development (Papaskiri et al., 2019). This further demonstrates that the impact of digital technology exhibits a threshold effect, which is fully realized only when a certain level of adoption is achieved. In addition, there is a significant influx of technological elements into rural areas, driven by the digital economy. However, this process is not linear; instead, it shows a marked threshold effect. The influx of technology resources does not dramatically increase until the digital economy reaches a certain stage of growth (Magomedov et al., 2020). The fifth and final factor is the flow of information variables and the informational links between rural and urban locations. The advancement of the digital economy has facilitated information exchange between these areas; however, the impact varies depending on the stage of development. The study highlights that information interconnectivity between urban and rural areas substantially improves once the digital economy surpasses a certain threshold (Wang et al., 2023).

Therefore, Hypothesis 3 suggests that the development of urban–rural integration is subject to a threshold effect depending on the level of digital economy advancement.

3.4 The digital economy's spatial spillover effects on urban–rural integration

The influence of a technical advancement or economic activity in one location that spreads to other places, producing wider economic and social advantages, is known as the "spatial spillover effect." In the digital economy, this effect involves the transfer of digital technology, information, and capital from one region to adjacent areas. Such transfer can stimulate economic growth and social development by expanding markets and disseminating technology. The digital economy significantly enhances regional innovation capacity and promotes growth in surrounding areas through technology diffusion and information exchange. Research indicates that the spatial spillover effect of China's digital economy is substantial, particularly in driving innovation and economic expansion in nearby cities (Huang X. et al., 2022). The growth of digital infrastructure, including broadband networks and data centers, has a spillover geographical impact as its second consequence. This infrastructure not only improves the local economic environment but also strengthens regional connectivity, thereby advancing the digital economy in neighboring areas. The expansion of broadband networks has been especially effective in fostering urban–rural integration and enhancing regional cohesion through increased information mobility and resource sharing (Xu S. et al., 2022). Third, there is the impact of digital finance on spatial distribution. The advancement of digital finance increases the efficiency of capital flows and allocations within regions, boosting local economic vitality. Moreover, it stimulates economic growth in nearby areas by expanding the reach of financial services. The study found that advancements in digital finance can have a significant positive impact on neighboring areas by boosting entrepreneurship and investment levels (Hao et al., 2023). Fourth, the impact of e-commerce and logistics networks on spatial distribution: The advancement of e-commerce and modern logistics networks has facilitated the transport of goods and services between urban and rural areas, thus enhancing regional economic development. E-commerce platforms not only boost the local economy but also extend market reach and stimulate economic activities in neighboring regions through network effects (Liu and Zhou, 2023). Furthermore, the growth of digital technology and information flows has created spatial spillover effects that support coordinated regional development. The digital economy has improved access to information and its swift dissemination, thereby contributing to the economic and social advancement of adjacent regions through the diffusion of knowledge and technology (Zhang Y. et al., 2023).

This brings to Hypothesis 4: Through geographical spillover effects, the digital economy may promote integrated urban and rural growth in neighboring regions.

4 Methodology and design

4.1 Model selection

4.1.1 Two-way fixed-effects model

This article uses the two-way fixed-effects model to examine how the amount of digital economy development (DEI) affects the level of urban–rural integration (URI). The key reasons for this choice are as follows: The two-way fixed-effects model is an effective tool for controlling both individual and time effects, which helps eliminate the confounding impacts of inter-provincial differences and time trends. This ensures the robustness and accuracy of the estimation results. In addition, the model reduces potential model specification errors and endogeneity issues, thereby providing more reliable conclusions. Given that this study utilizes provincial panel data, the two-way fixed-effects model is particularly suitable, as it leverages information from both the time and cross-sectional dimensions, thereby enhancing the generalizability of the research findings. Finally, the model's robustness can be verified through a series of tests, further strengthening the empirical analysis and providing a solid foundation for the study's conclusions. The model used in this study is constructed as follows:

$$URI_{i,t} = \alpha_0 + \alpha_1 DEI_{i,t} + \sum_k \alpha_k Control_{i,t} + \delta_i + \eta_t + \varepsilon_{it} \quad (1)$$

In equation 1, the explanatory variable URI_{it} is the measured level of urban–rural integration development; the core explanatory variable DEI_{it} is the measured composite index of digital economic development; $Control_{it}$ is a series of control variables; α is a parameter to be estimated; δ_{it} and η_{it} are the individual and time effects respectively; ε_{it} is a random disturbance term.

4.1.2 Mesomeric effect model

This study constructs multiple parallel mediating effects to test whether factor mismatch is a mediating variable between the digital economy and urban–rural integration. The reason for choosing a mediation effect model is that by constructing a multiple parallel mediation effect model, it is possible to deeply analyze the specific impact path of the digital economy on the development of urban–rural integration and, in particular, examine the mediating role played by factor mismatch. The digital economy may indirectly affect the level of urban–rural integration by optimizing the allocation of factors such as labor, capital, land, technology, and information. The mediating effect model can effectively identify and quantify this indirect impact. Drawing on the research methods of Baron and Kenny (1986), Judd and Kenny (1981), and Wen et al. (2004), the mediating effect analysis is carried out through the method of step-by-step test of regression coefficients. The specific testing steps are described as follows: First, in regression 1, it is necessary to verify whether the regression coefficient of the digital economic development index (DEI) on the degree of urban–rural integration (URI) passes the significance test, which is the basis of the whole testing process. Second, after confirming the significance of regression 1, the linear regression equation 2 is constructed, i.e., the regression equation of the digital economic development index (DEI) on the mediating variable factor mismatch level (MrF), to explore the effect of DEI on the factor mismatch level MrF. Finally, the regression equation 3 of the digital economic development index (DEI) and the mediating variable factor mismatch level (MrF) including on the degree of urban–rural integration (URI) is constructed to analyze whether the influence of DEI on URI changes after the introduction of the factor mismatch level (MrF) as a mediating variable, as well as the role of the factor mismatch level (MrF) in it.

$$MrF_{i,t} = \beta_0 + \beta_1 DEI_{i,t} + \sum_k \beta_k Control_{i,t} + \delta_i + \eta_t + \varepsilon_{it} \quad (2)$$

$$\begin{aligned} URI_{i,t} &= w_0 + w_1 DEI_{i,t} + w_2 MrF_{i,t} \\ &+ \sum_k w_k Control_{i,t} + \delta_i + \eta_i + \varepsilon_{it} \end{aligned} \quad (3)$$

In equations 2 and 3, $MrF_{i,t}$ represents the factor mismatch index; β is the estimated coefficient for the explanatory variable, which is the digital economic development composite index, on the mediator variable of factor mismatch; ω represents the effect of the factor mismatch mediator variable on urban–rural integration after accounting for the explanatory variable's impact from the digital economic development composite index.

4.1.3 Threshold effect model

To test Hypothesis 3 and further investigate the potential non-linear relationship between the digital economy and urban–rural integration, this study constructs a threshold regression model based on Hansen (1999) methodology. The main reason for choosing the threshold regression model is that the model is able to identify and portray the differential effects of urban–rural integration development under different levels of digital economy development. Specifically, by taking the level of digital economy development as a threshold variable, the threshold regression model can detect whether there are significant segmental changes in the impact of the digital economy on urban–rural integration development under different levels of digital financial inclusion development. This approach can not only reveal whether there is a critical point or threshold effect in the impact of the digital economy on urban–rural integration but also help us to understand the multiple paths of action of the digital economy on urban–rural integration at different stages of development, so as to provide more fine-grained policy recommendations.

$$\begin{aligned} URI_{it} &= c + \beta_1' index\_aggregatel\left(DEI_{it} \le \gamma \right) \\ &+ \beta_2' index\_aggregatel\left(DEI_{it} > \gamma \right) \\ &+ \lambda DEI_{it} + \delta_i + \eta_i + \varepsilon_{it} \end{aligned} \quad (4)$$

In equation 4, the core explanatory variable DEI_{it} is the threshold variable, where γ represents the threshold value. The coefficients β_1' and β_2' represent the impact of the explanatory variable on the dependent variable when $DEI_{it} \le \gamma$ and $DEI_{it} > \gamma$, respectively.

4.1.4 Spatial Durbin model

To evaluate hypothesis 4 and further investigate the spatial spillover effect of the digital economy on urban–rural integration and development, this study employed the spatial Durbin model (SDM) for analysis. The spatial Durbin model (SDM) is a commonly used spatial econometric model to analyze the spatial spillover effects of a variable, i.e., how changes in one region affect neighboring regions. Based on the common spatial autoregressive model (SAR) and spatial error model (SEM), the model further takes into account the spatial effects of the independent variables, thus capturing the interactions between regions more comprehensively (Bian et al., 2025). The Durbin model was selected for the following reasons: The SDM is well-suited to simultaneously account for spatial interactions between independent and dependent variables, capturing the spillover effects of the digital economy on urban–rural integration in neighboring areas and highlighting its geographical influence. It also handles spatial dependence and spatial autocorrelation, addressing the estimation bias that can arise from ignoring spatial factors in traditional models, thus ensuring result accuracy and interpretability. Furthermore, SDM enables the testing of both direct and indirect effects within the same model, offering more comprehensive insights into the impact mechanism of the digital economy on urban–rural integration and development. This makes SDM an ideal tool for studying the spatial effects of the digital economy, helping to uncover regional interactions and the mechanisms behind coordinated development.

$$URI_{it} = \alpha_0 + \rho \sum_{j=1}^{n} \omega_{ij} URI_{it} + \gamma DEI_{it} + \alpha \sum_{j=1}^{n} \omega_{ij} DEI_{it} + \beta Control_{i,t} + \theta \sum_{j=1}^{n} \omega_{ij} Control_{i,t} + \delta_i + \eta_t + \varepsilon_{it} \quad (5)$$

In equation 5, URI_{it} and DEI_{it} denote the explanatory variables and explanatory variables of province I, respectively; ρ is the explanatory variables' spatial autocorrelation coefficient, γ is the digital economy's regression coefficient, and α is the coefficient for the sector's spatial spillover effects; URI_{it} denotes the level of urban–rural integration of province j, $w_{ij}DEI_{it}$ is the spatial lag term of the urban–rural integration; w_{ij} is the spatial weighting matrix, which is used to synthesize and reflect the geographical linkage between inter-regional and economic and social connections between regions.

4.2 Variable selection

4.2.1 Explanatory variable

Urban–rural integration development level (URI): Urban–rural integration is a multidimensional integration of economic, humanistic, social, spatial, and ecological aspects. This study takes into account the multidimensional attributes of urban–rural integration, constructs an evaluation index system from five dimensions: spatial integration, population integration, economic integration, social integration, and ecological integration, and uses the entropy weight TOPSIS method for measurement. Spatial integration reflects the geographical and infrastructure integration between urban and rural areas through indicators such as urban and rural population density, urban road area ratio, urban and rural per capita private car ratio, and urban and rural spatial expansion, which directly affect the flow and sharing of resources. Population integration focuses on the degree of integration between urban and rural populations in terms of mobility, employment, and education. It measures the gap in economic activity and human capital accumulation between urban and rural areas through indicators such as the urbanization rate, urban–rural employment contrast coefficient, urban–rural education contrast coefficient, and the proportion of non-agricultural employed persons. Economic integration assesses the coordination of urban and rural economic activities through indicators such as the ratio of urban and rural per capita disposable income, the ratio of urban and rural per capita consumption, the dual structure comparison coefficient, and the ratio of urban and rural Engel's coefficient, which reflect the degree of integration of income, consumption levels, and economic structures between urban and rural areas. Social integration focuses on the equality and fairness of basic public services and social security for urban and rural residents through indicators such as the urban–rural medical conditions comparison coefficient, the urban–rural education and entertainment expenditure comparison coefficient, the social security expenditure ratio, and the urban–rural transportation and communication expenditure comparison coefficient. Finally, ecological integration reflects the degree of integration between urban and rural areas in terms of environmental protection and sustainable ecological development through indicators such as urban and rural ecological greening, urban and rural air pollution, urban and rural energy conservation and emission reduction, and urban and rural pollution control. Through this multidimensional index design, this study seeks to comprehensively and systematically measure the development level of urban–rural integration and provide a reliable basis for empirical analysis. The specific measurement process of the level of urban–rural integration is not repeated in the text because it is relatively mature (for details of the specific indicators and weight settings for the level of urban–rural integration, see Table 1).

4.2.2 Explanatory variable

Digital Economy Index (DEI): Drawing on the research ideas and methods of Wang et al. (2021) and Xu et al. W. (2022), this study designs a comprehensive indicator system from four dimensions: digital infrastructure, digital industrialization, industrial digitization, and digital innovation potential. The indicators are measured using the entropy weight TOPSIS method. Digital infrastructure is assessed using indicators such as the number of domain names, IPv4 addresses, Internet broadband access ports, and the length of optical cables per unit area. These indicators reflect the level of information and communication technology (ICT) infrastructure development in a region, which is fundamental for the digital economy's growth. A high level of digital infrastructure signifies broader network coverage and stronger communication capabilities, providing essential conditions for the digital economy's operation and expansion. Digital industrialization is measured by indicators such as the proportion of enterprises involved in e-commerce, per capita postal business income, per capita telecommunications business income, and per capita software business income. These indicators gauge the extent of digital technology's penetration and transformation within traditional industries. Digital industrialization indicates the practical application and commercialization of digital technology in economic activities and serves as a critical indicator for assessing the core industries of the digital economy. Industrial digitization is evaluated by factors such as the number of high-tech enterprises, the proportion of e-commerce sales in GDP, the number of information-based enterprises, and the digital inclusive finance index. This aspect of digitization promotes industrial modernization, enhancing efficiency and competitiveness through information technology, playing a pivotal role in high-quality economic development. Finally, digital innovation potential is assessed through indicators such as the digital innovation index, the number of digital innovation patents, the number of employees in scientific research and technical services, and R&D funding. This reflects a region's ability to innovate digitally and its future development prospects, representing the core driving force for sustained economic growth. Through these multidimensional indicators, this study provides a comprehensive and systematic approach to measuring the development level of the digital economy, offering a solid foundation for analyzing its impact on urban–rural

TABLE 1 Index system for urban–rural integration calculation.

First class index	Second class index	Weights	Tertiary class index	Weights	Indicator properties
Urban and rural areas integration level (URI)	Spatial integration (spaint)	0.2195	Urban population density	0.0656	+
			Urban road area ratio	0.0403	+
			Per capita ratio of private cars in urban and rural areas	0.0068	–
			Urban–rural spatial expansion	0.1068	+
	Population integration (popint)	0.1968	Urbanization rate	0.0555	+
			Urban–rural employment coefficient of inversion	0.0698	–
			Urban–rural education coefficient of inversion	0.0317	–
			Share of non-agricultural employed persons	0.0397	+
	Economic integration (econint)	0.1018	Comparison between urban and rural regions' per capita disposable income	0.0325	–
			Comparing urban and rural consumption per capita	0.0310	–
			Dual structure comparison coefficient	0.0158	–
			Urban–rural Engel's coefficient ratio	0.0225	+
	Social integration (socinte)	0.1431	Coefficient of comparison of medical conditions between urban and rural areas	0.0196	–
			Comparison of the expenditure on education and recreation between urban and rural areas	0.0180	–
			Social security expenditure comparison coefficient	0.0839	+
			The coefficient of comparison for transportation and communication costs in urban and rural locations	0.0216	–
	Ecological integration (ecolint)	0.3388	Ecological greening in urban and rural areas	0.0995	+
			Air pollution in cities and rural areas	0.0113	–
			Energy conservation and emission reduction in urban and rural areas	0.0221	–
			Management of pollution in urban and rural areas	0.2059	+

integration. The specific measurement process is well-established and thus not repeated here; for detailed indicators and weight settings (refer to Table 2).

4.2.3 Intermediary variable

As can be seen from the theoretical analysis above, the digital economy is not only a driving force for economic growth but also an important tool for achieving balanced urban–rural development. The digital economy plays an intermediary role in promoting the integrated development of urban and rural areas by optimizing the allocation of factors such as labor, capital, land, technology, and information. This optimization not only significantly improves the balance between urban and rural areas in terms of resource allocation efficiency but also promotes the in-depth and comprehensive development of urban–rural integration in various aspects such as the economy, society, and ecology. Therefore, this study measures the level of factor mismatch from five dimensions: labor, capital, land, technology, and information, and uses them as intermediary variables.

The spatial discrepancy between the supply and demand of factor resources is an external manifestation of the spatial mismatch of factor resources. Drawing on the relevant measurement methods of Le and Dai (2016) and Peng et al. (2022), the ratio of each province's specific factor to the nation's/province's GDP to the nation's GDP is used to define the level of spatial mismatch of factor resources (Le and Dai, 2016; Peng et al., 2022). To facilitate the econometric analysis, the formula can be transformed as follows (6):

$$MrF = \left| \frac{r_{it} / \sum r_{it}}{GDP_{it} / \sum GDP_{it}} - 1 \right| \tag{6}$$

The number of employed individuals in each province is the defining characteristic of the labor mismatch index (MLF); the capital mismatch index (MCF) is characterized by the total capital formation in each province; the land mismatch index (MLD) is characterized by the area of land supply for construction; the technology mismatch index (MTF) is characterized by the local financial expenditures on science and technology in each province; and the information mismatch index (MIF) is defined by the number of individuals employed in the information transmission service industry in each province.

4.2.4 Control variable

This study incorporates control variables that may influence the regression results, building upon the groundwork of prior research (Huang Y. et al., 2022). Industrialization level (IDL): represented by

TABLE 2 Index system for computing the digital economy.

First class index	Second class index	Weights	Tertiary class index	Weights	Calculation of indicators
Level of development of the digital economy (DEI)	Digital infrastructure (diginf)	0.2131	Total count of domain names	0.0057	+
			Total count of IPv4 URLs	0.0865	+
			Quantity of Internet broadband access ports	0.0390	+
			Length of fiber optic cable per unit area	0.0819	+
	Digital industrialization (digind)	0.3466	Proportion of businesses engaged in electronic commerce trade activities	0.0203	+
			Postal revenue per capita	0.1013	+
			Telecommunications revenue per capita	0.0825	+
			Software business revenue per capita	0.1426	+
	Industrial digitization (inddig)	0.2756	Number of high-tech enterprises	0.0902	+
			GDP share of e-commerce sales of enterprises	0.0453	+
			Number of informatization enterprises	0.1233	+
			The digital inclusive finance index	0.0168	+
	Digital innovation potential (diginn)	0.1647	Digital innovation index	0.0208	+
			Index of the number of patents granted for digital innovation.	0.0204	+
			Staffing level in technical and scientific fields	0.0444	+
			R&D investment	0.0791	+

the growth rate of assets of industrial enterprises above designated size. The level of industrialization is an important factor affecting the integration of urban and rural development. A higher level of industrialization usually means more employment opportunities and higher income levels, which may promote the migration of urban and rural residents to cities, thus affecting the process of urban–rural integration. Representing the level of industrialization by the growth rate of assets of industrial enterprises above designated size can better capture the changes in capital accumulation and production capacity in the industrialization process, which are directly related to the balance of urban and rural economic development. The degree of government intervention (DGI) is represented by the ratio of local general budget expenditure to regional GDP. The role of the government in the integration of urban and rural development is crucial. Through fiscal policy, infrastructure investment, and other measures, the government can directly influence the level of urban–rural development and the allocation of resources. Therefore, controlling the degree of government intervention helps identify the impact of the digital economy independent of government policies. The ratio of general budget expenditure of local finance to regional GDP is a common indicator to measure the degree of government intervention, reflecting the degree of government participation in economic activities. A higher ratio means that government intervention in the economy is more significant, which may affect the balance of urban–rural development. Innovation level (IOL): represented by the growth rate of domestic patent application authorizations. Innovation is an important driving force for economic growth and structural transformation. A high level of innovation is often accompanied by more advanced technology and higher production efficiency, which has a direct impact on urban–rural economic integration. Using the growth rate of domestic patent applications as an indicator of innovation level can reflect a region's scientific and technological innovation capabilities and the speed of technological progress, thereby providing a more comprehensive background for analyzing the impact of the digital economy on urban–rural integration. Industrial structure upgrading (ISU): represented by the ratio of tertiary industry growth to secondary industry value added. The sophistication of an industrial structure reflects the maturity and diversity of a region's economic development. The rise of the tertiary sector is usually accompanied by the development of the service industry and information technology, which are closely related to the digital economy and have a more direct impact on urban–rural integration. The ratio of the added value of the tertiary industry to that of the secondary industry can effectively measure the sophistication of an industrial structure, indicating the transformation of the economy from traditional industries to modern service industries. This transformation plays an important role in promoting the development of urban–rural integration. Education level (EL): represented by the number of students enrolled in colleges and universities per 10, 000 people. Education level affects the skills and knowledge of workers, which in turn affects the balance between supply and demand in the labor market as well as the mobility and integration of urban and rural populations. A higher education level is usually associated with higher economic participation and innovation capabilities. The number of students enrolled in colleges and universities per 10,000 people as an indicator of education level can reflect the accumulation of human capital in a region, which is crucial to understanding how the digital economy can promote the integrated development of urban and rural areas by upgrading human capital. Agricultural modernization level (AML): represented by per capita agricultural machinery power. The level of agricultural modernization is directly related to the development of the rural economy and the improvement of agricultural productivity. Regions with a higher level of agricultural modernization generally have stronger market competitiveness and higher income levels, which may promote the flow of resources between urban and rural areas and balanced development. Agricultural machinery power per capita is an important indicator for measuring the level of agricultural modernization, reflecting the degree of mechanization of agricultural production. By controlling for this variable, the impact of the digital economy on urban–rural integration in regions with different levels of agricultural development can be better understood. By selecting and controlling for these variables, this study can more accurately examine the impact of the digital economy on the development of urban–rural integration and rule out other factors that may interfere with the results, thereby ensuring the robustness and interpretability of the research results.

4.2.5 Instrumental variable

There might be a causal link between the growth of the digital economy and urban–rural integration. In addition, this study could encounter endogeneity issues due to the omission of certain variables. To address potential endogeneity problems arising from reverse causality and omitted variables, the study employs the instrumental variable technique. In addition to adhering to the criteria of exogeneity and relevance, this research develops two distinct instrumental variables based on historical and geographical views, respectively.

For the historical instrumental variables, drawing on existing research, the number of post offices per 10,000 people in 1984 (IV1) (Bai and Yu, 2021; Yu et al., 2023) and fixed telephones per 10,000 population in 1984 (IV2) (Qian et al., 2020; Huang B. et al., 2023), is an instrumental variable for the level of development of the digital economy. Building on the ideas of Huang et al. (2019), the adoption of Internet technology initially began with the widespread use of telephony, indicating that the digital economy's growth also originates from the proliferation of landline phones (Huang et al., 2019). In other words, areas with higher landline penetration rates are also likely to have better digital economies. Furthermore, post offices serve as the operational branch for landline deployment. Historically, the number of post offices has influenced the subsequent development of Internet technology, thus affecting the growth of the local digital economy. As a result, the condition of instrumental variable relevance is satisfied. In addition, the presence of post offices and landline telephones per 10,000 people in 1984 did not significantly impact the amount of urban–rural integration between 2011 and 2022. Therefore, the condition of instrumental variable exogeneity is satisfied. The level of urban–rural integration from 2011 to 2022 was not significantly impacted by this factor, therefore fulfilling the condition of exogeneity for instrumental variables. Geographical instrumental variables refer to the spherical distance between the province capital city and Hangzhou, denoted as IV3 (Zhang et al., 2019, 2020) was selected as an instrumental variable for the level of digital economy development, drawing on existing studies. Hangzhou is a prominent city in the advancement of the digital economy due to its association with Alibaba, which is a prime example of the digital economy and has its origins in Hangzhou. Provinces nearer to Hangzhou encounter fewer obstacles in accessing digital technology and achieve higher levels of digital economic development, satisfying the correlation requirement of the instrumental variable. Moreover, geographical distance is less correlated with the current state of urban–rural integration, fulfilling the exogeneity requirement for the instrumental variable.

Since the three chosen instrumental variables are cross-sectional data, they are unsuitable for econometric analysis involving panel data. To address this, the article refers to the approaches used by Huang et al. (2019) and Zhang et al. (2020). These methods involve calculating the product of the number of post offices per 10,000 people in 1984, the number of fixed-line telephones per 10,000 people in 1984, and the spatial distance from the capital city to Hangzhou with the level of digital economic development measured using the entropy method. The panel data, which were obtained by independently multiplying the annual mean values, were analyzed using instrumental variables.

4.2.6 Data sources and descriptive statistics

The panel data of 30 provinces, municipalities, and autonomous regions in China from 2011 to 2022 are selected as the research sample for this study (Tibet, Hong Kong, Macao, and Taiwan are not included in this study due to the large amount of missing data). The raw data used in this study mainly come from statistical information with high authority and reliability, including China Statistical Yearbook, China Rural Statistical Yearbook, China Environmental Statistical Yearbook published by the National Bureau of Statistics of China, and China Digital Inclusive Finance Index published by the Digital Finance Research Center of Peking University. In addition, some of the data come from local statistical yearbooks. For the few missing data, this study used the common data processing method of linear interpolation to fill in the blanks. The descriptive statistics for the variables are shown in Table 3.

5 Examining the spatial and temporal trends in the digital economy and the integration of urban and rural areas

5.1 Overall trends in the scope of the digital economy and the level of urban–rural integration across different times and regions

The development indicators for the digital economy and urban–rural integration are examined in this article along with their temporal patterns and the advancements made in each of their dimensions. China's digital economy has shown consistent progress, demonstrating a positive trend in its development. From 2011 to 2022, the average value of China's Digital Economy Index (DEI) has nearly doubled. Nevertheless, it is important to highlight that the industrial digitization (inddig) index had a significant decrease in 2021, which had a noticeable impact on the Digital Economy Development Index (DEI). The three indicators of digital infrastructure (diginf), digital industrialization (digind), and digital innovation potential (diginn) all exhibited a consistent and uninterrupted increase trajectory (refer to Figure 1). The data suggest that China's digital economy is expanding, establishing a strong basis for future digital advancements.

China's urban–rural integration has consistently improved over the study period, as indicated by the levels of integration. The average urban–rural integration level (URI) shows a variable upward trend from 2011 to 2022 (see Figure 2). The data show a peak in 2014, followed by a drop from 2014 to 2018, and a subsequent modest recovery after 2018. However, when considering the average value as a whole, the level of urban–rural integration during the study period was

TABLE 3 Variable description and descriptive statistics.

Category of variables	Variable name	Definition and assignment	Sample size	Mean	standard deviation	Maximum values	Upper quartile
Explained variables	Rural–urban integration (URI)	Measured by the entropy right TOPSIS method	360	0.3280	0.0470	0.5700	0.3300
Explanatory variables	Digital economy (DEI)	Measured by the entropy weight TOPSIS method.	360	0.0323	0.0270	0.1500	0.0200
Mediating variables	Labor factor mismatch (MLF)	Calculated from related studies	360	0.3693	0.2570	1.1200	0.3300
	Capital factor mismatch (MCF)	Calculated by drawing on related studies	360	0.3896	0.4180	2.2500	0.2600
	Land factor mismatch (MLD)	Calculated by drawing on related studies	360	0.3304	0.3740	1.8800	0.2000
	Technology factor mismatch (MTF)	Calculated by drawing on relevant studies	360	0.3846	0.2780	1.6000	0.3700
	Information factor mismatch (MIF)	Calculated by drawing on relevant studies	360	0.6444	0.7600	4.7900	0.4300
Control variables	Industrialization level (IDL)	Asset growth rate of industrial enterprises above large scale	360	0.0876	0.0660	0.2500	0.0800
	Degree of government intervention (DGI)	General Budget Expenditure of Local Finance/Gross Regional Product	360	0.2589	0.1120	0.7600	0.2300
	Innovation level (IOL)	Growth rate of domestic patent applications and authorizations	360	0.2295	0.2090	1.0400	0.2100
	Industrial structure upgrading (ISU)	Value added of the tertiary sector/ value added of the secondary sector	360	1.3536	0.7450	5.2800	1.2000
	Education level (EL)	Enrollment rate in general higher education institutions per 10, 000 individuals	360	0.0210	0.0060	0.0400	0.0200
	Level of agricultural modernization (AML)	Per capita power of agricultural machinery	360	0.7461	0.4180	2.2900	0.6800

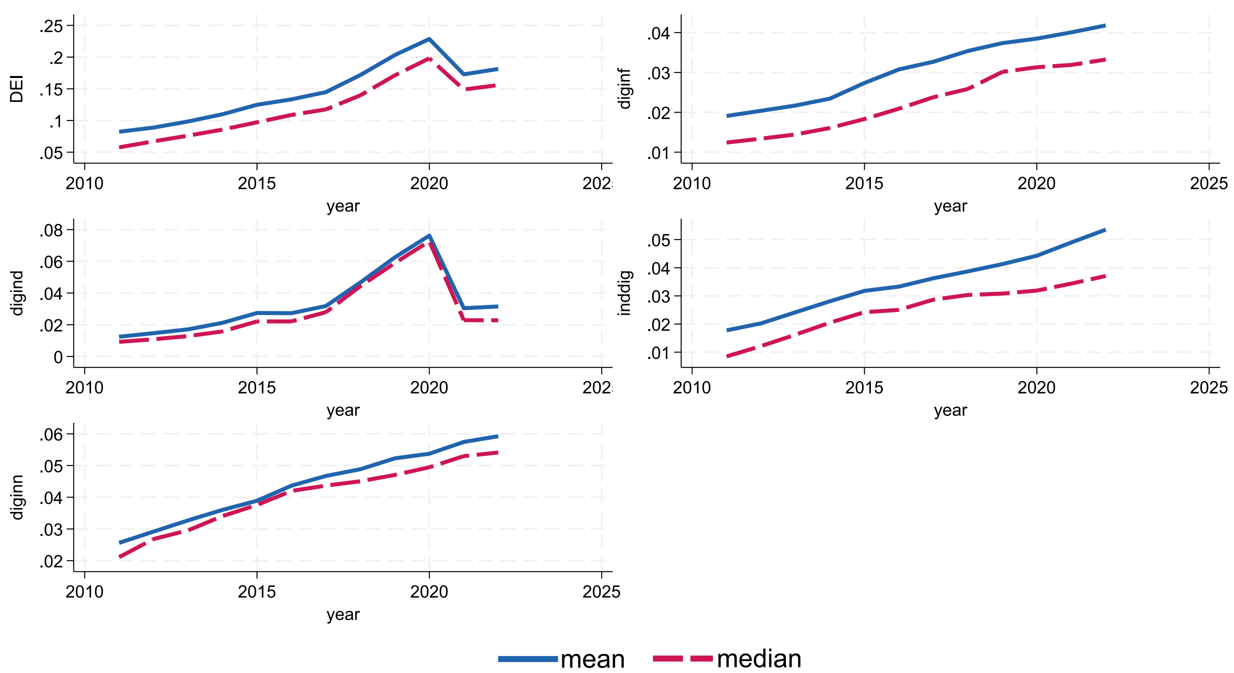

FIGURE 1
China's digital economy development level: A temporal trend from 2011 to 2022.

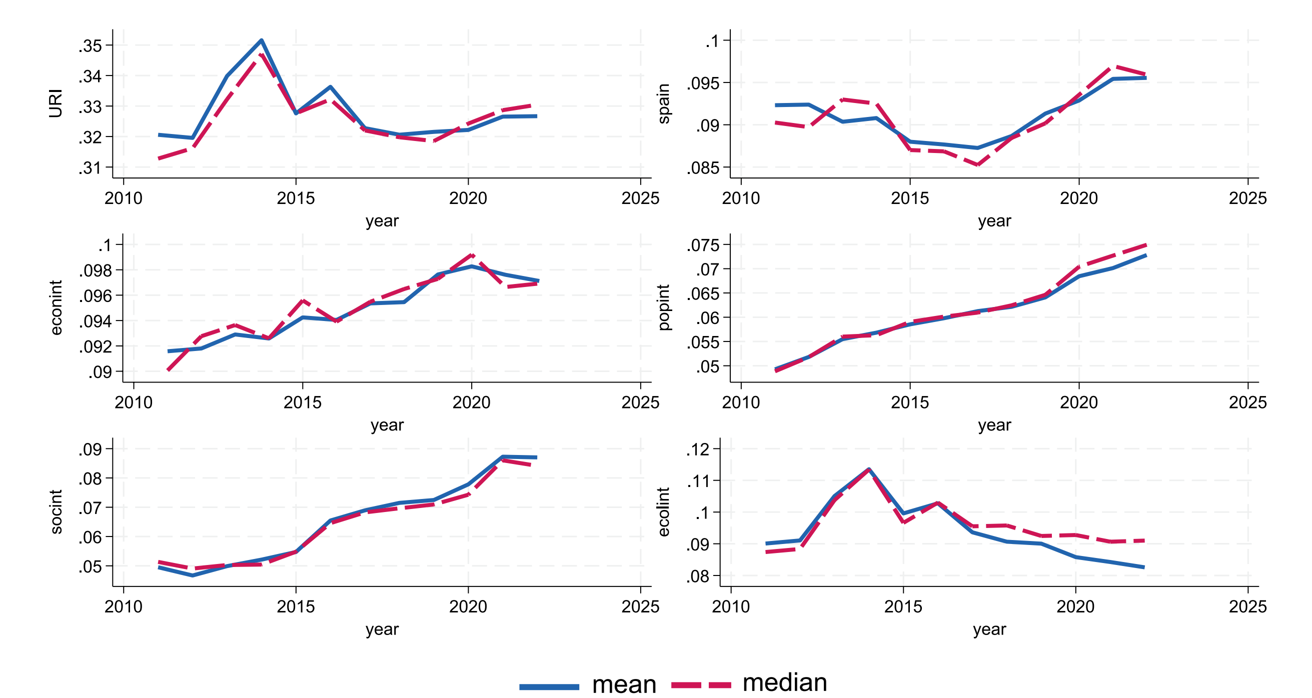

FIGURE 2
Temporal trends in urban–rural integration development levels in China from 2011 to 2022.

only approximately 0.3. This indicates that the overall level of urban–rural integration is currently low, and the issue of imbalanced urban–rural development remains significant. The level is at approximately 0.3, indicating that China currently has a low level of total urban–rural integration. Furthermore, uneven urban–rural growth is still a major problem. The four dimensions of spatial integration (spaint), demographic integration (popint), economic integration (econint), and social integration (socinte) have consistently shown an upward trajectory in terms of subdimensions. Nevertheless, ecological integration (ecoint) has undergone variations. China's degree of urban–rural integration and development remained comparatively low during the course of the research period. The main causes of this were the rigid and methodical urban–rural dual structure in China, the one-way flow of resources into cities, and the gradual slowdown in the growth of rural regions. Integration and development between urban and rural areas remain a long-term historical challenge.

The study utilizes the natural breakpoint method to classify the levels of digital economy development and urban–rural integration development from 2011 to 2022 into five distinct regional types, based on spatial trends. The presentation is visualized using ArcGIS software. The categories are high-value areas, higher-value areas, medium-value areas, lower-value areas, and lower-value areas (refer to Figures 3, 4). Overall, the level of digital economy development shows a decreasing trend of gradient of "East-Central-West." During the study period, China's high level of digital economy has gradually spread inland from the coastal areas, and gradually formed two cores of Sichuan Province and eastern coastal provinces, with obvious spatial differentiation. In 2011, the only high-value areas with advanced levels of digital economy development were Beijing, Shanghai, and Guangdong. By 2015, provinces such as Qinghai, Heilongjiang, Liaoning, and Hainan transitioned from low-value to lower-value regions, while the higher-value areas remained unchanged; in 2019, the high-value areas added Zhejiang and Jiangsu; by 2022, the level of digital economic development in the provinces has jumped significantly, and the eastern coastal provinces have become high-value and higher-value agglomeration areas, the central provinces have become the medium-value area of agglomeration, and the southwestern region has formed a Sichuan-centered growth trend, and the northwest and northeast regions remain in a low development state.

Figure 4 illustrates significant inter-provincial differences in urban–rural integration levels, highlighting distinct "convergence" and "divergence" patterns. The overall distribution of China's urban–rural integration development during the study period reveals a pattern of "high in the northeast and southwest, low in the northwest, and intermediate in the central regions," with a marked divergence along the "Hu Huanyong Line" serving as the boundary. This spatial trend analysis indicates that the high-value areas for both digital economy and urban–rural integration show contrasting distribution trends. Consequently, it is important to consider whether the digital economy positively influences the improvement of urban–rural integration levels.

5.2 Temporal regional convergence of the digital economy and urban–rural integration

5.2.1 α convergence model

σ convergence can measure the degree of deviation of the level of digital economy development or urban–rural integration development in different provinces relative to the overall mean and portray whether such deviation shows a converging trend over time, i.e., whether the inter-regional differences are narrowing. From the results of the σ convergence index of digital economy (see Figure 5A), China's digital economy development level shows an obvious regional

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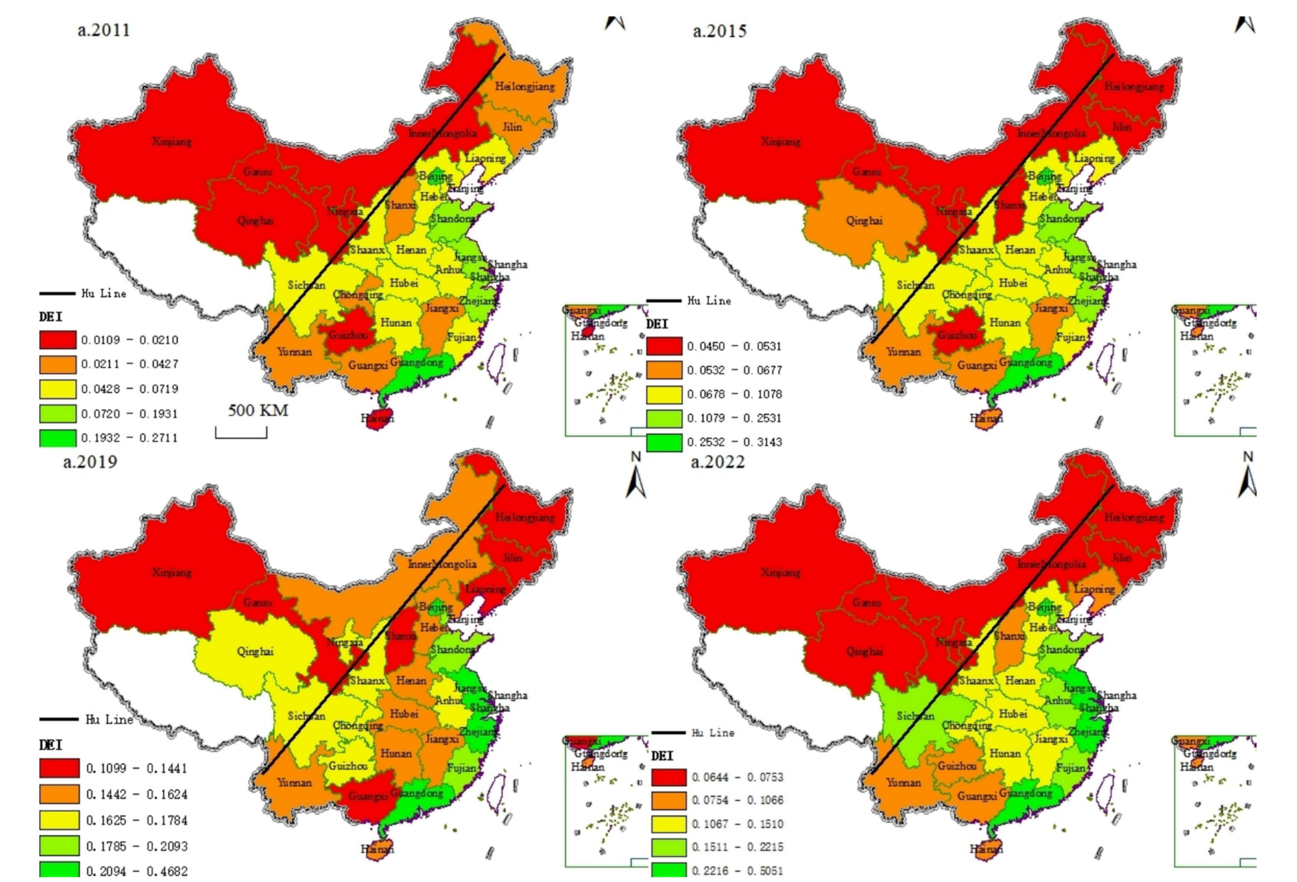

FIGURE 3
Spatial variation characteristics of China's digital economy development level from 2011 to 2022.

convergence trend during the study period. Specifically, the σ convergence index decreases from 0.968 in 2011 to 0.678 in 2022, indicating that the dispersion of the level of digital economy development among provinces is gradually decreasing, i.e., the development differences among different regions are narrowing. This trend may be influenced by factors such as policy guidance at the national and local levels, increased infrastructure investment, technology diffusion effects, and increased market integration. However, it is worth noting that the trajectory of the σ convergence index in the figure is not monotonically decreasing, especially during 2019–2021, and the index fluctuates to a certain extent and picks up after reaching a stage low in 2020. This may be related to changes in the global economic environment, domestic industrial restructuring, and differences in the pace of implementation of specific policies. Therefore, despite the overall trend of convergence, it may still be disturbed by external shocks or structural factors in the short term. Taken together, the findings support the hypothesis of σ convergence of the digital economy at the provincial level, i.e., the level of digital economy development is equalizing across regions. However, in the future, attention still needs to be paid to inter-regional policy coordination, optimization of resource allocation and bridging of the digital divide to further promote balanced development at the national level.

The results of the σ-convergence index of urban–rural integrated development (see Figure 5B) show that the level of China's urban–rural integrated development has generally shown a trend of convergence over the study period, meaning that the differences in the level of urban–rural integrated development between different regions have been gradually narrowing. Specifically, the σ convergence index decreases from 0.145 in 2011 to 0.118 in 2022, indicating that the degree of dispersion in the level of urban–rural integration and development has decreased. This trend may be closely related to various factors such as the promotion of integrated urban–rural development at the national level, the rural revitalization strategy, and the policy of equalization of public resources. With the continuous promotion of infrastructure construction, public service provision, and collaborative industrial development, the development gap between urban and rural areas has been bridged to a certain extent. However, judging from the trend of index change, the convergence process of urban–rural integration is not a linear decline, but a brief rise between 2013 and 2015, followed by an oscillating downward trend and some fluctuations between 2019 and 2021. This may reflect the uneven development of urban–rural convergence, with some regions differing in the pace of urban–rural convergence due to factors such as industrial base, population mobility, and policy implementation efforts. In addition, the fluctuation of the index after 2020 may be affected by external shocks, such as changes in the global economic environment and the impact of the new crown epidemic on the urban–rural industrial structure and labor mobility. Overall, the findings validate the σ convergence trend of urban–rural integrated development, i.e., the urban–rural development gap is narrowing. However, the fluctuations in the short term indicate that the problem of uneven

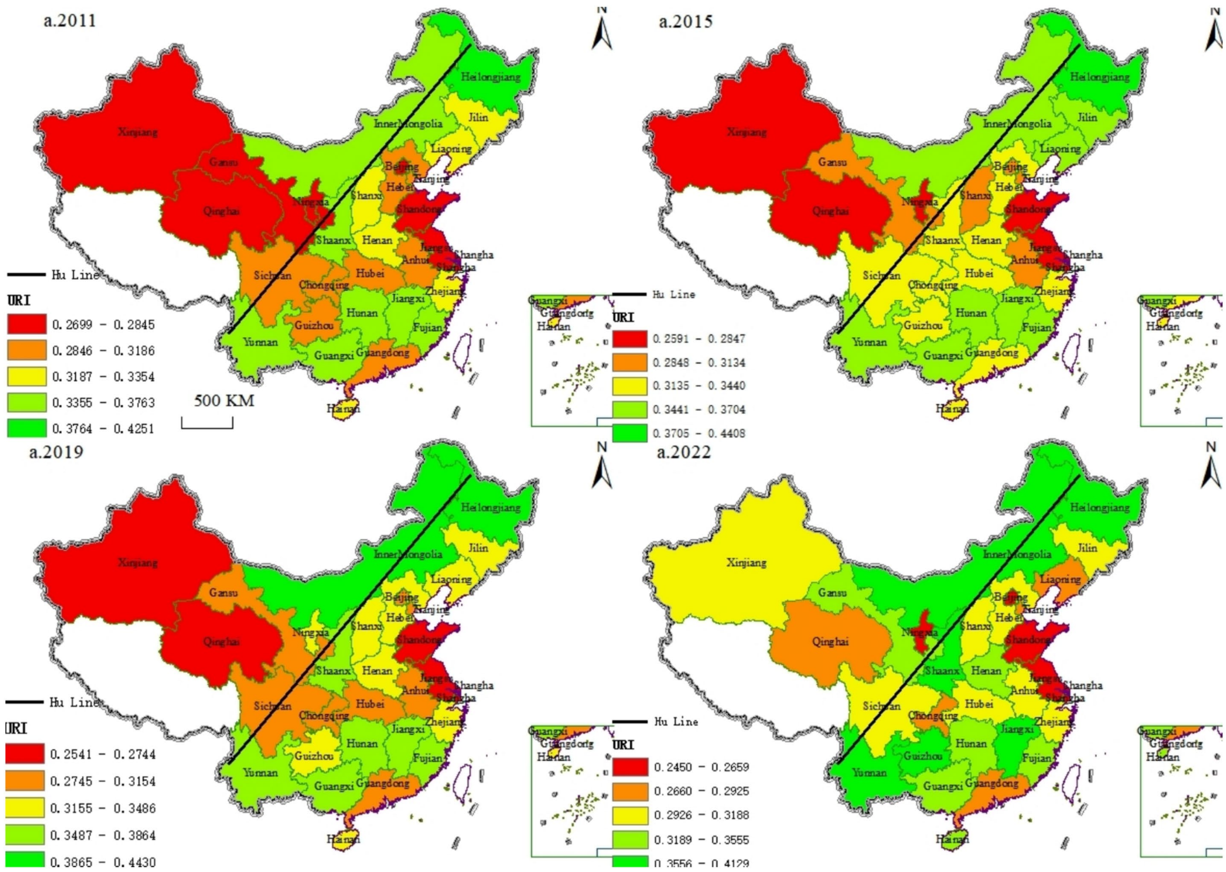

FIGURE 4
Spatial variation characteristics of urban–rural integration development level in China from 2011 to 2022.

FIGURE 5
(A) α-convergence index of China's digital economy from 2011 to 2022. **(B)** α-convergence index of urban–rural integration from 2011 to 2022.

development between regions still exists. Therefore, in the future, there is a need to further strengthen urban–rural policy synergy, optimize resource allocation, and promote the equalization of basic public services between urban and rural areas, so as to ensure the long-term sustainable development of urban–rural integration.

5.2.2 Absolute β-convergence

Absolute β-convergence pertains to the inclination of less advanced regions in the progression of the digital economy or urban–rural integration to narrow the gap with more advanced regions, under the assumption of no other factors. The regression results (see Table 4) show that the coefficient of absolute convergence, β, is significantly negative. This suggests the presence of absolute β-convergence in the disparities in digital economy development levels between regions. Furthermore, it indicates that regions with lower indices of digital economy development experience higher growth rates.

The regression analysis on urban–rural integration, as presented in Table 5, indicates that the absolute convergence coefficient β is significantly negative. This indicates the presence of absolute β-convergence in the levels of urban–rural integration and

TABLE 4 Absolute β-convergence of China's digital economy.

	Index growth rate
Log (DEIit)	−0.1120*** (0.0170)
Constant term	−0.1660*** (0.0390)
N	300

Standard errors in parentheses, *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

TABLE 5 Absolute β-convergence of urban–rural integration in China.

	Index growth rate
Log (URIit)	−0.0670* (0.0350)
Constant term	−0.0730* (0.0390)
N	300

Standard errors in parentheses, *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

development across different regions. Specifically, regions with lower initial urban–rural integration and development indexes tend to experience higher growth rates.

Overall, there is clear evidence of substantial regional convergence in the advancement of the digital economy and the integration of urban and rural areas over the study period. This suggests that the disparity in digital economy development and urban–rural integration among various regions is progressively diminishing, thereby supporting the promotion of coordinated regional development.

5.3 Spatial digital economy and geographical clustering of urban–rural integration

5.3.1 Global Moran index

Global Moran's I is a quantitative metric used to evaluate spatial interdependence among spatial units. As shown in Table 6, the Global Moran's I for digital economy development consistently remains above 0 and is statistically significant from 2011 to 2022. This indicates that the digital economy exhibits significant geographical autocorrelation, suggesting that neighboring regions display spatial interdependence in their levels of digital economy development. More precisely, areas that have a significant degree of advancement in the digital economy tend to group together, just as regions with lower degrees of progress do. During the study period, there was a noticeable increase in the Global Moran's I from 0.1720 to 0.2290, indicating a significant rise in spatial agglomeration within the digital economy.

The analysis of Global Moran's I (see Table 7) indicates that from 2011 to 2022, the Global Moran's I for urban–rural integrated development was positive and statistically significant. This indicates a significant positive spatial autocorrelation in urban–rural integration, meaning neighboring regions demonstrate spatial dependence in digital economy development. More specifically, areas that exhibit high and low degrees of urban–rural integration tend to be grouped together. Global Moran's I increased from 0.1830 to 0.3890 during the course of the research period, indicating an increasing trend in the degree of geographical clustering of urban–rural integrated development. The worldwide Moran's I grew from 0.1830 to 0.3890 throughout the research period, suggesting an increasing trend in the geographical clustering of integrated urban–rural development.

5.3.2 Localized Moran index

The digital economy's local Moran scatter plot (refer to Figure 6) shows both high–high and low–low clustering patterns, indicating a notable geographical clustering impact of the sector's growth in China throughout the research period. High–high clusters are primarily located in Shanghai, Jiangsu, Zhejiang, and Shandong, whereas low–low clusters are mainly found in the western regions. High–low areas are predominantly in Beijing and Guangdong, while low–high areas are mainly distributed across the central regions. The spatial distribution centers of these clusters have not significantly changed, highlighting the "Matthew Effect" in current digital economic development. To address the imbalance, comprehensive strategies, policy coordination, and regional cooperation are needed to promote a comprehensive, balanced, and sustainable digital economy development pattern.

As shown in Figure 7, the Local Moran scatter plot of urban–rural integration illustrates the gradual emergence of spatial diffusion effects in China's urban–rural integration development. Throughout the study period, China's digital economic development exhibited significant local spatial clustering effects, with high–high (diffusion and spillover) and low–low (slow growth) clusters being predominant. Provincially, high–high clusters were primarily located in the northeastern and southwestern provinces, while low–low clusters were mainly found in the northwestern and southeastern coastal provinces. The high–low and low–high clusters were mainly concentrated in the eastern regions. Over time, the spatial distribution of these cluster types changed, with high–high clusters gradually shifting to the central regions, while high–low clusters moved eastward and low–high clusters expanded westward. The low–low clusters' center of gravity remained in the northwest. This pattern reflects the significant potential for regional coordinated development in China. To create a mutually advantageous urban–rural network system, it is imperative to further boost urban–rural integration by augmenting the dispersion effects of regional growth and facilitating the bidirectional movement of urban and rural components.

6 Results of empirical tests of the impact of the digital economy on urban–rural integration

6.1 Benchmark regression results

The Hausman test results indicate that fixed effects are used to estimate the benchmark model (1), with the corresponding findings presented in Table 8. Table 8 benchmark regression demonstrates that the growth of the digital economy has had a substantial and beneficial impact on the integration of urban and rural areas in China's provinces and regions during the research period. The results of bidirectional fixed-effects regressions with new control factors are displayed in columns (2)–(7) of Table 8. These results show that the favorable impact of the digital economy on urban–rural integration remains considerable, even after considering these control variables. This affirms that the fundamental findings of this study are resilient, remaining valid even when new factors are taken into account.

TABLE 6 Spatial autocorrelation Moran index of China's digital economy.

Year	Moran's I	E (I)	Sd (I)	Z	*P*-value
2011	0.1720	−0.0345	0.1180	1.7400	0.0819
2012	0.1920	−0.0345	0.1180	1.9090	0.0562
2013	0.1870	−0.0345	0.1190	1.8670	0.0618
2014	0.2200	−0.0345	0.1190	2.1360	0.0327
2015	0.2410	−0.0345	0.1190	2.3080	0.0210
2016	0.2430	−0.0345	0.1200	2.3220	0.0202
2017	0.2480	−0.0345	0.1200	2.3620	0.0182
2018	0.2280	−0.0345	0.1190	2.2120	0.0270
2019	0.2180	−0.0345	0.1180	2.1420	0.0322
2020	0.2090	−0.0345	0.1180	2.0730	0.0382
2021	0.2390	−0.0345	0.1190	2.3090	0.0209
2022	0.2290	−0.0345	0.1180	2.2270	0.0260

TABLE 7 Spatial autocorrelation Moran index of urban–rural integration in China.

Year	Moran's I	E (I)	Sd (I)	Z	*P*-value
2011	0.1830	−0.0345	0.1240	1.7560	0.0792
2012	0.1720	−0.0345	0.1240	1.6590	0.0970
2013	0.3750	−0.0345	0.1230	3.3160	0.0009
2014	0.2880	−0.0345	0.1140	2.8280	0.0047
2015	0.3560	−0.0345	0.1220	3.1950	0.0014
2016	0.2100	−0.0345	0.1120	2.1870	0.0287
2017	0.3740	−0.0345	0.1220	3.3390	0.0008
2018	0.2530	−0.0345	0.1220	2.3480	0.0189
2019	0.3000	−0.0345	0.1210	2.7560	0.0058
2020	0.3540	−0.0345	0.1210	3.2150	0.0013
2021	0.3980	−0.0345	0.1190	3.6220	0.0003
2022	0.3890	−0.0345	0.1200	3.5140	0.0004

The regression findings in column (7) indicate that there is no statistically significant association between the degree of government involvement (DGI) and the development of urban–rural integration. This suggests that government involvement may not yet be strong enough to significantly impact urban–rural integration or that there could be a delay in the effects of these programs. Moreover, the relationship between the level of education (EL) and urban–rural integration growth is not statistically significant, possibly due to disparities in educational resource allocation among different regions. However, the coefficient for industrialization level (IDL) shows a strong positive correlation, suggesting that higher levels of industry have a favorable effect on urban–rural integration. This phenomenon can be attributed to various factors, including increased job prospects, upgraded infrastructure, reinforced economic relationships between urban and rural areas, and improved distribution of technology and information. Industrialization is a significant factor in improving living standards and promoting the blending of social structures and cultures. The coefficient for innovation level (IOL) is positively significant, indicating that technological innovation plays a vital role in driving urban–rural integration. Furthermore, the coefficient for industrial structure upgrading (ISU) exhibits a notably favorable value. This shows that modernizing industrial infrastructure makes it easier to integrate resources and markets from rural and urban areas. It also creates more interconnected industrial and supply chains, enhances material flows and information exchanges, deepens economic interdependence, and promotes overall urban–rural economic integration. Moreover, the coefficient for agricultural modernization level (AML) shows a significant positive correlation, indicating that agricultural modernization is crucial for promoting urban–rural integration. This is achieved by boosting agricultural production capacity, diversifying the rural economy, and improving rural infrastructure and living conditions for farmers.

6.2 Robustness check

To ensure the reliability and validity of the regression results, this study conducts robustness tests from three key aspects: variable substitution, endogeneity treatment, and sample adjustment. These robustness checks help verify the stability of the empirical findings and mitigate potential biases in the estimation process. The methodology is shown below:

6.2.1 Substitution of variables

The primary objective of achieving comprehensive urban–rural integrated development is to promote the growth of urban–rural economic integration. Therefore, this article proposes using the economic integration (econint) sub-dimension index as a replacement for the explanatory variable of urban–rural integration level (Zhao et al., 2023). Therefore, this study uses the digital infrastructure (diginf) sub-dimensional index as a proxy for the explanatory variables. The regression results for these proxy variables are shown in columns (1) and (2) of Table 9, where the significance of the regression coefficients remains largely unchanged.

6.2.2 Addressing endogenous issues

The instrumental variable least squares (IV-2SLS) method is also employed. The results for the instrumental factors are presented in Table 10. The Hausman test confirms that the digital economy variable (DEI) is endogenous. The Kleibergen-Paap rk LM test indicates no issues with under-identification. The Wald, Kleibergen-Paap, and redundancy tests confirm the absence of weak instruments. The Hansen J test further validates the choice of instruments, confirming that all three instrumental variables are exogenous. The regression coefficients from the IV-2SLS estimates, presented in column (3) of Table 9, maintain the same sign and significance as the benchmark regression.

6.2.3 Changing the regression sample

The omission of municipalities from the regression sample is another factor considered. To address potential bias from regional economic disparities and variations in policy preferences, this study excludes four municipalities—Beijing, Tianjin, Shanghai, and Chongqing—from the empirical testing sample. The coefficients and the significance of the estimation results in column (4) of Table 9

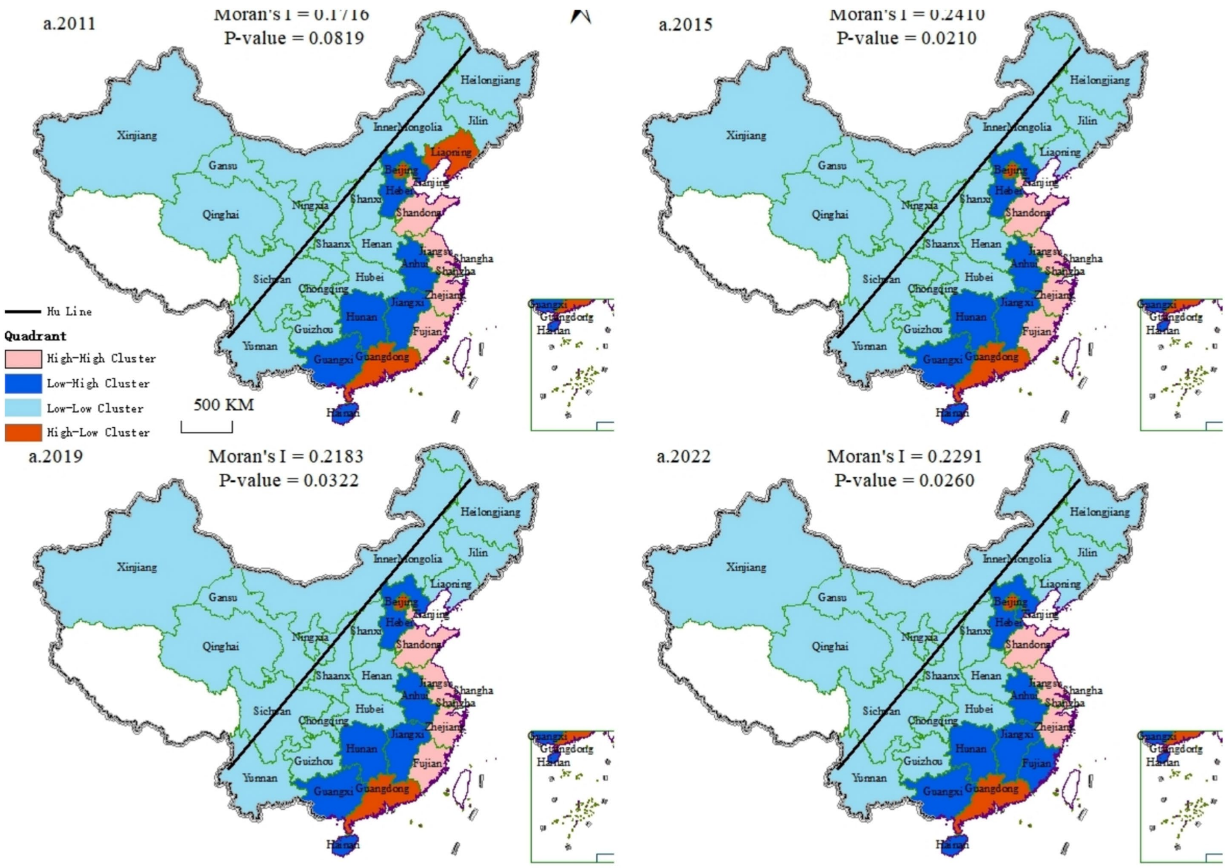

FIGURE 6
Moran scatter plot of China's provincial digital economy from 2011 to 2022.

remain highly consistent with those of the baseline regression. The robustness test further confirms the resilience of the benchmark regression findings. Therefore, we can conclude that the first hypothesis is correct: The rise of the digital economy is contributing to the integration of urban and rural areas in China.

6.3 The mechanism test of digital economy influencing rural–urban integration development under resource factor allocation

This study utilizes a multiple parallel mediation effect model to confirm the theoretical claim that the digital economy enhances urban–rural integration by optimizing the allocation of resources. This study investigates the potential of the digital economy to decrease disparities across different factors and thereby improve the integration between urban and rural areas. The outcomes of the stepwise regression mediation effect test, shown in Table 11, indicate the following: The impact of the digital economy on factor mismatches. The computed coefficients for digital economy variables in Columns (2), (4), (6), (8), and (10) demonstrate a statistically significant negative relationship. This suggests that advancements in the digital economy contribute to reducing disparities in labor, capital, land, technology, and information resources. The digital economy variables in Columns (3), (5), (7), (9), and (11) have a considerably favorable effect on urban–rural integration, as indicated by the computed coefficients. The bootstrap test verifies the statistical significance of the mediating impact of factor mismatch. These findings indicate that the favorable effects of the digital economy on the development of urban–rural integration are somewhat influenced by the efficient distribution of resources, including labor, capital, land, technology, and information. The coefficient for technological factor mismatch (MTF) in Column (9) lacks statistical significance when considered alone. Nevertheless, the confidence range derived from the Bootstrap test does not encompass zero, suggesting that the coefficient product is statistically significant and that there is evidence of a mediating influence. Sequence of Mediating Effects: The ratio of the mediating impact to the total effect provides a measure of the relative effectiveness of addressing factor mismatches. The order of improvement in factor mismatches is as follows: Technology factor mismatch improvement is superior to labor factor mismatch improvement, which is superior to information factor mismatch improvement, capital factor mismatch improvement, and land factor mismatch improvement. This order signifies that the ongoing progress of the digital economy has a significant impact on enhancing discrepancies in technology, labor, and information variables, which are already well-developed and optimized.

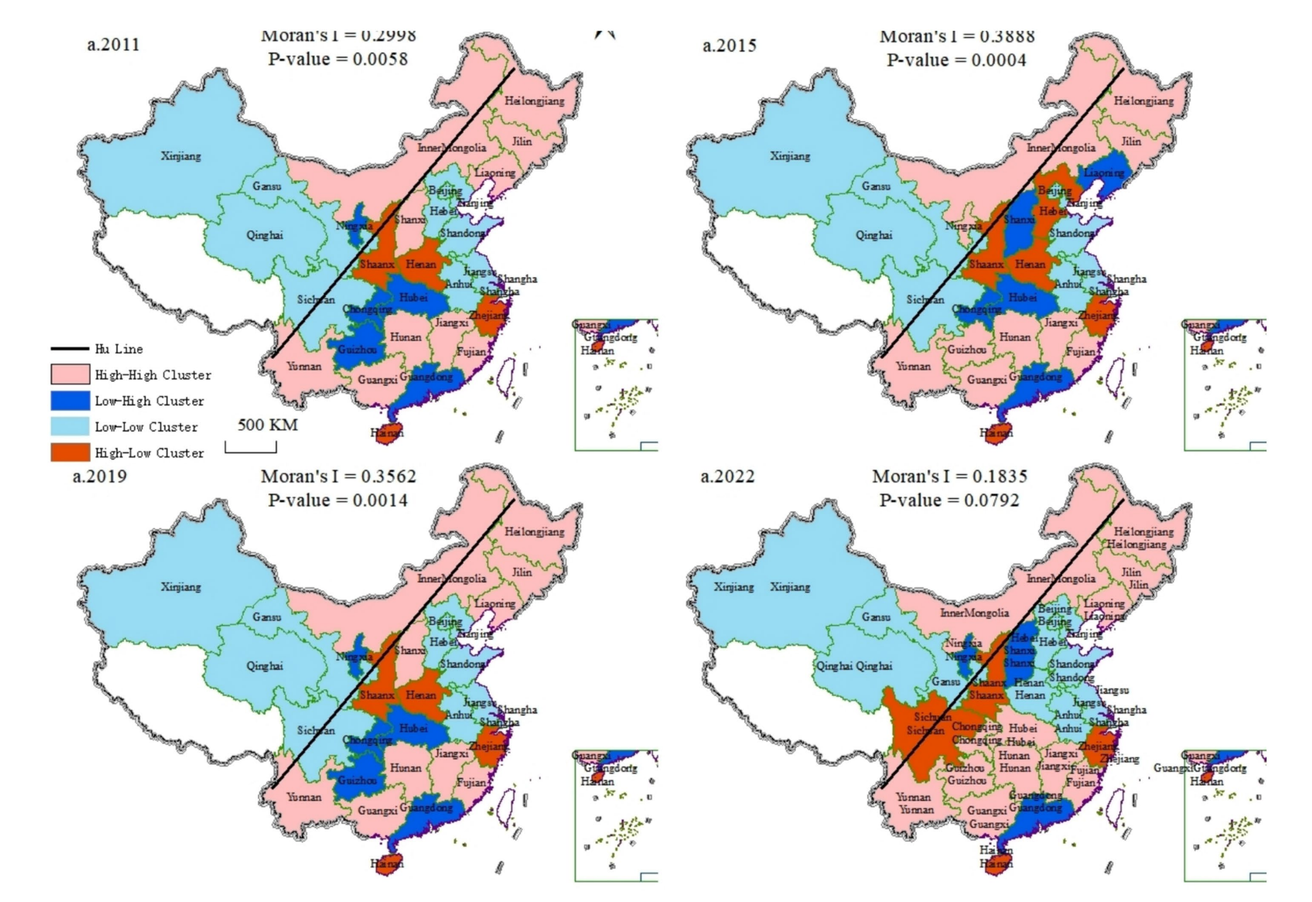

FIGURE 7
Moran scatter plot of provincial urban–rural integration from 2011 to 2022.

The findings of the mediation effect test support the theory that, by improving resource allocation, the digital economy promotes the integration of urban and rural communities. More specifically, there is a transmission mechanism that makes the digital economy's influence on urban–rural integrated development possible by assisting in the reduction of component mismatches, which in turn promotes integrated development between urban and rural regions. Increasing Allocation Efficiency: The digital economy effectively increases how efficiently resources such as labor, money, land, technology, and information are allocated. This optimization enhances the seamless movement of urban and rural resources and enables effective allocation of resources across borders.

Thus, it has been shown that the second hypothesis—that the digital economy improves resource allocation and so indirectly promotes urban–rural integration—is true.

6.4 The multifaceted impacts of the digital economy on urban–rural integration and development

To examine the linear relationship between the digital economy and the level of urban–rural integration and development, we ran a regression test in the preceding section. This research uses Hansen (1999) technique to assess the possibility that the digital economy significantly affects the progress of urban–rural integration (Hansen, 1999). Furthermore, this method enables us to determine the number of thresholds and establish the precise structure of the threshold model. The test results for the threshold effect are presented in Table 12. Using the degree of growth of the digital economy as the threshold variable, the *p*-values for the single, double, and triple threshold models are 0.000, 0.063, and 0.212, respectively. It is noteworthy that the p-values for the single and double threshold models are statistically significant, while the triple threshold model fails the test. As a result, the double-panel threshold model is used in the related investigation. The likelihood ratio test plot and threshold estimate are shown in Figure 8. The plot of the likelihood ratio test indicates that the threshold value is statistically significant with a confidence level of 95%. The test findings show that there is a non-linear relationship between urban–rural integration and the digital economy. Put another way, the degree of urban–rural integration varies according to the state of the digital economy.

The threshold model's estimate results are shown in Table 13. The findings show that the digital economy development level is split into three periods by the 2-fold threshold model. This shows that there may be a two-threshold influence on how the growth of the digital economy affects urban–rural integration. More specifically, the effect of the digital economy on advancing urban–rural integration

TABLE 8 Baseline regression results.

Variable	Two-way fixed effect						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
DEI	0.7570*** (3.58)	0.6368*** (2.95)	0.5888*** (2.74)	0.5942*** (2.78)	0.4994** (2.28)	0.6767*** (2.67)	0.7842*** (3.04)
Level of industrialization (IDL)		0.0797** (2.35)	0.0720** (2.13)	0.0647* (1.92)	0.0613* (1.82)	0.0685** (2.02)	0.0680** (2.01)
Level of government intervention (DGI)			0.1569** (2.47)	0.1479** (2.34)	0.0910 (1.30)	0.0873 (1.25)	0.0814 (1.17)
Innovation level (IOL)				0.0215** (2.26)	0.0219** (2.31)	0.0221** (2.34)	0.0246** (2.59)
Industrial structure advanced (ISU)					0.0209* (1.87)	0.0224** (2.01)	0.0192* (1.71)
Education level (EL)						1.7653 (1.38)	1.6897 (1.32)
Agricultural modernization level (AML)							0.0232** (2.02)
Constant term	0.3099*** (54.35)	0.2992*** (41.23)	0.2621*** (15.76)	0.2609*** (15.78)	0.2556*** (15.29)	0.2202*** (7.18)	0.2081*** (6.69)
	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	12	12	12	12	12	12	12
Number of periods	30	30	30	30	30	30	30
Number of provinces	360	360	360	360	360	360	360
Number of observations	0.0442	0.0576	0.0725	0.0844	0.0916	0.0942	0.1030
R2	4.7997	4.9193	5.0773	5.1391	5.0757	4.9020	4.9019

t-values in parentheses, *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

TABLE 9 Robustness test results.

Variable	Substitution of explanatory variables	Substitution of explanatory variables	IV-2SLS	Excluding municipalities
	(1)	(2)	(3)	(4)
DEI	0.0859**		2.8916***	0.8083***
	(2.13)		(5.58)	(2.65)
diginf		1.4789**		
		(2.63)		
	Yes	Yes	Yes	Yes
Control variables Constant term	0.0234***	0.2095***	0.0840*	0.2234***
	(4.05)	(3.89)	(1.74)	(6.96)
	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	12	12	12	12
Number of periods	30	30	30	26
Number of provinces	360	360	360	312
N	0.7600	0.2051	0.6331	0.1437
R2	33.8639	3.1488		5.2886

Unless otherwise indicated, *t*-values in parentheses, *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

TABLE 10 Instrumental variable test results.

Variables	Phase I	Phase II
Instrumental variable IV1	39.4667***	
	(11.0640)	
Instrumental variable IV2	0.0007*	
	(0.0004)	
Instrumental variable IV3	−0.0002***	
	(0.0000)	
Digital economy DEI		2.8916***
		(0.5182)
Hausman test statistic	13.36	
	(p = 0.0003)	
Kleibergen-Paap rk LM statistic	54.8540	
	(p = 0.0000)	
Kleibergen-Paap rk Wald F statistic	14.5540	
	(F = 12.83)	
Redundancy test LM statistic	54.854	
	(p = 0.0000)	
Hansen J test statistic	3.5687	
	(p = 0.1679)	
Constant term	0.03520***	0.0840*
	(0.0062)	(0.0482)
Control variables	Yes	Yes
Province fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Number of periods	12	12
Number of provinces	30	30
Number of observations	360	360
R2	0.9679	0.6811

t-values in parentheses unless otherwise indicated, *p < 0.1, **p < 0.05, and ***p < 0.01.

eventually wanes as it develops beyond the two thresholds that have been established. Once the second threshold is reached, the impact of this factor becomes statistically negligible. This phenomenon may be explained by the relationship that exists between the growth of the digital economy and the "digital dividends" that urban regions get and the "digital resources" that rural areas accumulate. However, the challenge is converting these digital resources into a competitive advantage, which leads to a widening gap between urban and rural areas and impedes urban–rural integration. This growing disparity has slowed the progress of integrating urban and rural areas.

The double threshold effect may be due to the relationship between the growth of the digital economy and the "digital dividend" accruing to urban areas and the "digital divide" accumulating in rural areas. Urban areas have gained a greater advantage due to higher levels of digital infrastructure and technology adoption, while rural areas have struggled to keep pace. Digital innovation tends to benefit urban economies, which already have well-developed infrastructure and human capital, thus exacerbating pre-existing inequalities in access to resources and economic opportunities (Yan et al., 2023). Inadequate technological literacy, low levels of entrepreneurial activity, and weak policy support in rural areas hinder the transformation of digital resources into competitive advantages in rural areas. As a result, digital innovation may inadvertently exacerbate socioeconomic disparities rather than alleviate them (Esteban-Navarro et al., 2020). Policymakers must therefore implement strategic interventions to bridge the digital divide, such as targeted digital literacy programs, infrastructure investments, and encouragement of technology-enabled rural entrepreneurship. In the absence of such measures, the rural–urban divide may continue to widen, hindering the equitable distribution of the benefits of the digital economy and thus slowing down the process of rural–urban integration.

6.5 Analyzing the impact of the digital economy on the integration and development of urban and rural areas, specifically focusing on the geographical spillover effects

The LM test and R-LM test indicate the simultaneous presence of both the spatial error and spatial lag effects. The LR test, Wald test, and log-likelihood suggest that the spatial Durbin model (SDM) is the most suitable choice. In addition, the Hausman test concludes that a fixed-effects model is more appropriate. Consequently, the fixed-effects SDM is selected for further analysis. The regression results of the spatial error model (SEM) and the spatial autoregressive model (SAR) are also reported for comparison (See Table 14).

This research built a two-way fixed-effects spatial Durbin model (SDM) using the spatial adjacency matrix; Table 15 shows the regression findings. The SDM results show that the spatial autoregressive coefficient ρ for urban–rural integration is significantly positive, indicating a strong positive spatial correlation. This suggests that improvements in urban–rural integration in one area can positively affect neighboring regions, enhancing their integration levels as well. The coefficient for the digital economy index is also significantly positive, indicating that the digital economy has a substantial positive effect on local urban–rural integration. As the level of digital economic development increases, so does the degree of urban–rural integration, reflecting the critical role of digital technology and economic activity in reducing the urban–rural divide, promoting resource sharing, and enhancing overall socioeconomic development.

Furthermore, the regression coefficient for the lagged digital economy is significantly positive, indicating that the digital economy has a positive spatial spillover effect on urban–rural integration in neighboring provinces. This finding implies that the development of the digital economy in one region can enhance its urban–rural integration while positively influencing adjacent areas. This occurs through the dissemination of technology, the flow of talent, and the spread of capital, thereby fostering urban–rural integration in neighboring provinces. The results from the spatial error model (SEM) and the spatial autoregressive model (SAR) further validate this conclusion.

To further investigate the spatial spillover effects of the digital economy, this study draws on the research of LeSage and Pace and

TABLE 11 Mediation effect test results of factor misallocation.

Variant	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	URI	MLF	URI	MCF	URI	MLD	URI	MTF	URI	MIF	URI
DEI	0.7842***	−4.8735***	0.9712***	−5.9658***	0.6970***	−1.8376*	0.8393***	−4.8173***	0.7301***	−7.0741**	0.8847***
	(−3.04)	(−6.16)	(−3.57)	(−2.98)	(−2.68)	(−1.71)	(−3.26)	(−2.98)	(−2.79)	(−2.10)	(−3.46)
MLF			0.0384**								
			(−2.09)								
MCF					−0.0146**						
					(−2.01)						
MLD							0.0300**				
							(−2.22)				
MTF									−0.0112		
									(−1.24)		
MIF											0.0142***
											(−3.32)
N	360										
Total effect	0.7842										
Mediating effect		−0.187		0.0872		−0.0551		0.7301		−0.1005	
Direct effect		0.9712		0.6970		0.8393		0.0541		0.8847	
Mediated effect percentage		23.85%		11.12%		7.03%		93.10%		12.82%	
Bootstrap test confidence interval		[−0.708, −0.2110]		[−0.725, −0.2173]		[−0.8114, −0.2994]		[0.4107, 1.2541]		[−0.7865, −0.3024]	

Unless otherwise indicated, *t*-values in parentheses, *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

TABLE 12 Threshold effect test results.

Threshold variables	Threshold number	Threshold value	*F*-value	P-value	Number of BS	Threshold value		
						10%	5%	1%
DEI	Single Threshold	0.0080	55.01	0.0000	1,000	19.3910	22.9399	31.9292
	Double Threshold	0.0137	23.94	0.0630	1,000	20.6935	25.8912	39.5290
	triple threshold	0.0073	19.43	0.2120	1000	29.0759	41.2027	59.3927

P-values and critical values were obtained by Bootstrap sampling 1,000 times.

employs partial differential methods to decompose the estimated results of the spatial Durbin model into direct and spillover effects (LeSage and Pace, 2009). The direct effects reveal that the coefficient measuring the impact of the digital economy on local urban–rural integration is significantly positive, confirming that digital economic development effectively enhances local integration. Regarding indirect effects, the spatial spillover of the digital economy on the urban–rural integration of neighboring provinces is also significantly positive. This indicates that the digital economy positively influences integration in surrounding areas through spatial connectivity. The effect decomposition of the SAR regression supports this conclusion, validating Hypothesis 4.

6.6 An empirical test of the regional heterogeneity of the impact of digital economy on urban-rural integration development

Using a classification system based on economic geography and the degree of progress in digital technology, this research intends to investigate the variations in the growth of China's digital economy and its effects on urban–rural integration. It then uses fixed-effects spatial Durbin model (SDM) to examine how the digital economy affects the integration of urban and rural areas in various geographies. More precisely, the report categorizes the area into Eastern, Central, and

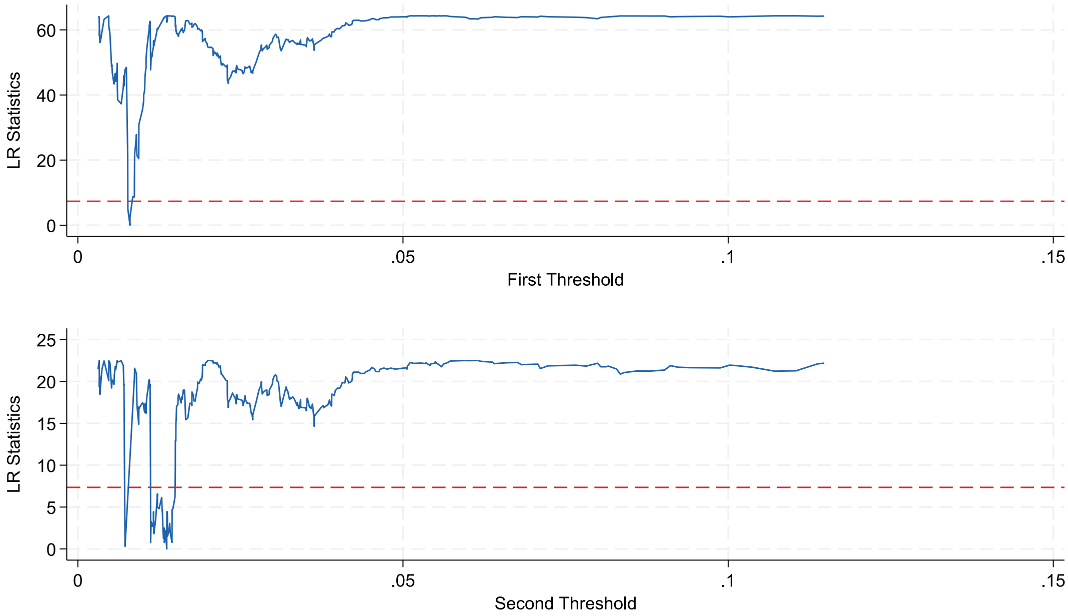

FIGURE 8
Threshold estimation values and likelihood ratio test plot.

TABLE 13 Threshold effect estimation results.

Variant	(1) Two-way fixed effect	(2) Double threshold
DEI	0.7842*** (3.04)	
DEI ≤ 0.0080		9.6849*** (8.60)
0.0080 < DEI ≤ 0.0137		2.2141*** (4.74)
DEI > 0.0137		0.3205 (1.32)
Control variable	Yes	Yes
Constant term	0.2081*** (6.69)	0.1966*** (5.94)
Province fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
N	360	360
R2	0.1030	0.2547
F	4.9019	8.5834

t-values in parentheses, **p* < 0.1, ***p* < 0.05, and ****p* < 0.01.

TABLE 14 Spatial panel model test.

Test methods	Statistic	*P*-value
LM (SEM)	63.8320	0.0000
LM (SAR)	14.8160	0.0000
R-LM (SEM)	53.2720	0.0000
R-LM (SAR)	4.2560	0.0390
LR (SEM)	6.3000	0.5057
LR (SAR)	5.7000	0.5749
Wald (SEM)	6.3500	0.4990
Wald (SAR)	5.7300	0.5713
Log-likelihood (SDM)	841.7879	
log-likelihood (SEM)	838.6402	
Log-likelihood (SAR)	838.9367	
Hausman (SDM)	54.5100	0.0000

Western areas according to China's three primary economic zones.[2] From an economic geography perspective, the study area was divided into three major regions in China: eastern, central, and western. Furthermore, based on the level of digital technology development, the study area was categorized into Internet-developed, developing, and underdeveloped regions, determined by the average Internet coverage during the study period.[3]

The regression analysis demonstrates that the coefficients, total effects, and direct effects of the digital economy are all significantly positive in all three types of regions. This suggests that the digital economy plays a major role in promoting urban–rural integration in these regions (See Table 16). In regions with advanced Internet

2 Eastern region: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; Central region: Shanxi, Inner Mongolia, Anhui, Jiangxi, Henan, Hubei, Heilongjiang, Jilin, and Hunan; Western region: Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

3 Internet developed areas: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Zhejiang, Fujian, Hubei, Guangdong, and Xinjiang; Internet developing areas: Shanxi, Inner Mongolia, Jilin, Heilongjiang, Jiangsu, Jiangxi, Shandong, Chongqing, Shaanxi, and Qinghai; Internet less developed areas: Anhui, Henan, Hunan, Guangxi, Hainan, Sichuan, Guizhou, Yunnan, Gansu, and Ningxia.

development, both the coefficients for the lagged term and the spatial spillover effect are significantly positive. This indicates that the growth of the digital economy in these technologically proficient areas positively impacts urban–rural integration in nearby provinces through spatial effects. Conversely, areas with limited or underdeveloped Internet infrastructure have not shown comparable spillover effects. Underdeveloped regions may encounter constraints such as poor infrastructure, insufficient resource consolidation, low economic activity intensity, and less favorable policy conditions. These limitations hinder the growth of the digital economy in these areas and reduce its influence on surrounding regions. As a result, these regions may lack the necessary internal and external incentives to promote the widespread adoption of digital technology and enhance urban–rural integration, leading to an absence of significant spatial effects.

TABLE 15 Spatial spillover effects of the digital economy on urban–rural integration development.

Variant	(1)	(2)	(3)
	SDM	SAR	SEM
DEI	0.7038*** (2.73)	0.6347*** (2.68)	0.6159*** (2.62)
WxDEI	0.2737** (2.20)		
Control variables	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Spatial ρ	0.2559*** (3.51)	0.2615*** (3.78)	
Spatial λ			0.2664*** (3.70)
Variance σ2	0.0005*** (13.30)	0.0005*** (13.31)	0.0005*** (13.30)
DEI direct effects	0.7415*** (2.75)	0.6552*** (2.65)	
DEI spillover effect	0.5665** (1.30)	0.2146** (2.07)	
DEI total effect	1.3080** (2.28)	0.8697*** (2.67)	
N	360	360	360
Log-likelihood	841.7879	838.9367	838.6402

t-values in parentheses, $*p < 0.1$, $**p < 0.05$, and $***p < 0.01$.

However, while the positive effects of digital innovation are evident in many regions, it is equally important to recognize its potential negative impacts. One major challenge is the digital divide, where wealthier, well-connected urban areas benefit more from technological progress, while underdeveloped rural areas struggle to keep pace. Studies indicate that regions with limited technological infrastructure experience lower rates of digital innovation adoption, leading to increased economic and social disparities between urban and rural areas. In addition, while digital transformation fosters economic growth, it can also lead to the marginalization of traditional industries in rural regions that rely on manual labor. To address these challenges, the principles of Responsible Research and Innovation (RRI) provide a framework for ensuring that digital economic growth is inclusive, ethical, and sustainable. RRI emphasizes the importance of policy interventions, stakeholder collaboration, and equitable access to digital resources to prevent widening inequalities. Governments and institutions should strengthen policy support for rural digital development, invest in education programs to enhance digital literacy, and encourage community-driven technological initiatives to ensure that digital innovations benefit both urban and rural populations equitably.

The Eastern, Central, and Western regions exhibit strong positive spatial correlations in economic and geographical integration between urban and rural areas. In addition, the digital economy significantly benefits local urban–rural integration. More precisely, the growth of the digital economy in the central region has resulted in a beneficial transfer of economic activity to other provinces, leading to improved integration between urban and rural areas. Nevertheless, the Eastern and Western regions have not exhibited

TABLE 16 Analyzing how the digital economy influences the growth of urban–rural integration in different regions.

Variant	(1)	(2)	(3)	(4)	(5)	(6)
	Internet-enabled regions	Internet developing regions	Less developed areas of the Internet	Eastern part	Central region	Western region
DEI	0.886*** (3.70)	0.803** (3.27)	1.055*** (4.18)	0.892*** (3.75)	1.050*** (4.36)	0.875*** (3.49)
WxDEI	1.273* (2.20)	0.122 (0.21)	−0.104 (−0.24)	0.475 (1.27)	1.451** (2.67)	−0.0431 (−0.07)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Spatial ρ	0.236** (3.18)	0.264*** (3.68)	0.289*** (4.08)	0.279*** (3.90)	0.2825*** (3.99)	0.2672*** (3.75)
Variance σ2	0.0005*** (13.37)	0.0006*** (13.42)	0.005*** (13.53)	0.0005*** (13.39)	0.0005*** (13.43)	0.0006*** (13.42)
DEI direct effects	0.872*** (3.55)	0.814** (3.22)	1.067*** (4.10)	0.894*** (3.65)	1.054*** (4.29)	0.885*** (3.44)
DEI spillover effect	0.285* (1.88)	0.0284 (0.19)	−0.0385 (−0.29)	0.112 (0.84)	0.409* (2.38)	−0.0163 (−0.09)
DEI total effect	1.157*** (4.21)	0.842** (2.97)	1.028*** (3.70)	1.006*** (3.96)	1.464*** (4.84)	0.869* (2.55)
N	120	120	120	132	108	120
Log-likelihood	841.1542	838.5059	846.4354	842.657	845.3512	838.6034

t-values in parentheses, $*p < 0.1$, $**p < 0.05$, and $***p < 0.01$.

comparable spillover effects. To rectify these inequalities, it is imperative to foster a more equitable distribution of digital infrastructure investments, particularly in rural regions, and increase digital skill development programs to ensure that local populations can leverage technological advancements. A collaborative approach involving knowledge sharing, resource allocation, and inter-regional partnerships will be essential to achieving nationwide urban–rural integration, ensuring that the benefits of digitalization are widely distributed rather than concentrated in specific areas.

7 Discussion and conclusion

This study examines how the digital economy promotes urban–rural integration by optimizing factor allocation, systematically analyzing its mechanisms, spatial effects, and policy implications, with a focus on China's experience.

7.1 The role of the digital economy in urban–rural integration

The findings indicate that the digital economy has significantly contributed to urban–rural integration by improving resource allocation efficiency and reducing factor mismatches in labor, capital, land, and technology. Advanced digital infrastructure and Internet penetration have facilitated the seamless flow of resources between urban and rural areas, fostering regional economic connectivity (Deng et al., 2023). However, the impact of digital economic development exhibits a non-linear threshold effect—at initial stages, its role in urban–rural integration is limited, but once a critical threshold is crossed, the positive effects intensify. Beyond a second threshold, diminishing marginal returns become apparent, highlighting the need for adaptive policy frameworks that align with different stages of digital development (Jakobsen et al., 2019).

The spatial spillover effects of digital innovation are also evident as regions with advanced technological infrastructure experience positive externalities that enhance integration in neighboring areas. This effect is particularly strong in economically developed regions, where interconnectivity allows for the diffusion of technology, skills, and capital. Conversely, in underdeveloped areas, weak infrastructure, inadequate policy support, and limited digital literacy hinder the diffusion of digital economic benefits, exacerbating regional disparities (Yan et al., 2023).

7.2 The positive and negative effects of digital innovation

While the digital economy has brought significant positive effects, such as increased efficiency, employment opportunities, and rural revitalization, it has also introduced several challenges that need to be addressed. On the positive side, digital platforms have reduced information asymmetry, enabled small rural businesses to access larger markets, and enhanced financial inclusion through mobile banking and fintech solutions (Zhang Z. et al., 2023). In addition, e-commerce and digital payment systems have lowered transaction costs, fostering greater integration between urban and rural economies (Buonocore et al., 2024). However, negative externalities persist. One of the most pressing issues is the digital divide, where urban centers benefit disproportionately from digital advancements, while rural areas struggle with inadequate access to high-speed Internet and digital skills training. This exacerbates socioeconomic inequalities and creates regional imbalances in digital economic development (Shirazi and Hajli, 2021). Moreover, digital transformation poses threats to traditional employment, as automation and AI-driven solutions replace low-skilled jobs, disproportionately affecting rural labor markets (Luo and Zhu, 2024).

7.3 The role of responsible research and innovation in mitigating the digital divide

To ensure that digital innovation supports inclusive and sustainable urban–rural integration, the framework of Responsible Research and Innovation (RRI) must be incorporated into policy design. RRI emphasizes ethical considerations, public engagement, and long-term sustainability in the innovation process. In the context of digital economy-driven urban–rural integration, RRI provides a structured approach to mitigate potential risks while maximizing social benefits (Deng et al., 2023).

Key RRI principles relevant to digital economic growth include the following: Equitable Access: Ensuring that rural areas receive targeted investments in digital infrastructure and digital literacy programs. Stakeholder Engagement: Encouraging participation from local governments, private enterprises, and rural communities in shaping digital development strategies. Sustainability and Ethics: Implementing regulatory frameworks that prevent monopolistic control over digital markets and protect data privacy rights. Implementing RRI-driven policies can help prevent widening inequalities and ensure that digital innovation contributes to balanced, long-term urban–rural integration (Jakobsen et al., 2019).

7.4 Policy implications and future directions

Given the findings, several policy recommendations emerge: Strengthening Digital Infrastructure: Governments should prioritize investments in rural broadband networks and smart infrastructure to bridge the digital divide. Promoting Digital Literacy and Workforce Training: Establishing training programs to equip rural populations with the necessary skills to participate in the digital economy. Fostering Regional Collaboration: Facilitating technology transfer and knowledge sharing between developed and underdeveloped regions to promote more equitable digital economic growth. Implementing Inclusive Digital Governance: Policymakers must adopt RRI-based regulations that ensure fair access to digital opportunities while mitigating the risks of technological displacement. Future research should explore the long-term impacts of digital innovation on income distribution and labor markets, particularly in rural settings. In addition, interdisciplinary studies that integrate economic, social, and technological perspectives will be valuable in refining policy approaches for sustainable urban–rural integration.

8 Conclusion

This study provides empirical evidence that the digital economy significantly influences urban–rural integration by optimizing factor allocation and fostering spatial spillovers. However, its benefits are not evenly distributed, and without targeted interventions, digital innovation may exacerbate regional inequalities. By incorporating RRI principles and implementing strategic policy measures, governments can ensure that digital transformation serves as an inclusive and sustainable force for regional development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YL: Formal analysis, Funding acquisition, Methodology, Writing – original draft. JZ: Writing – review & editing, Visualization. LL: Writing – review & editing. MK: Supervision, Validation, Visualization, Writing – review & editing. CY: 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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