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Exploring the effects of ICT on urbanization in China: evidence from a provincial spatial panel data model

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The study investigates the intricate relationships between ICT and urbanization through the application of spatial panel data models. The analysis is based on data collected from 31 provincial cities in China over the period from 2012 to 2021. The emergence, diffusion, and influence of ICT exert dynamic and varied impacts on demographic, spatial, and economic aspects of urbanization. For estimation, a Spatial Durbin Model (SDM) is employed. The findings from the SDM indicate that ICT has both positive and negative effects on urbanization. Not all regions can swiftly reap the benefits of ICT, leading to an exacerbation of the digital divide and uneven development across regions. Nevertheless, less developed areas are actively seeking strategies to bridge the existing gap and leverage the advantages offered by ICT. Furthermore, the study reveals that the impacts of ICT on economic urbanization is significant. Key ICT indicators related to the ICT environment, application level, and achievement are crucial in driving urbanization development. The study serves as a valuable reference for policymakers assessing the multifaceted impacts of ICT on urbanization and formulating appropriate policies to enhance the positive effects of ICT.

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Introduction

Urbanization is inevitably accompanied by technological advancement. With increasing innovation and diffusion of information and communication technology (ICT), urbanization tends to be rapid and dramatic, emphasizing the importance of high-quality and sustainability (Goel and Vishnoi 2022; Zhao et al. 2023). ICT plays an essential and influential role in urbanization by facilitating the exchange of information, knowledge, and services among different sectors in urban areas. It also enhances urbanization by improving the efficiency, productivity, and innovation of urban activities and systems, such as industry, energy, health, education, and governance (Fernández-Gutiérrez et al. 2020; Gómez-Fernández and Mediavilla 2021; Haldar et al. 2023; Hussain et al. 2021; Kim et al. 2021; Kosec and Wantchekon 2020; N'dri et al. 2021; Saba and Ngepah 2022; Zhang et al. 2022a). ICT creates opportunities for more compact, connected, and inclusive cities. More generally, ICT can be considered a tool for countries to boost urbanization by improving the economy and reshaping spatial patterns and social dynamics (Kozma 2005).

ICT empowers countries worldwide, but the impacts of ICT on countries are multifaceted and complex (Polák 2017; Stanley et al. 2018). On the one hand, ICT contributes to enhancing access to information, improving communication, and fostering social inclusion (Cui et al. 2017). On the other hand, ICT poses challenges to urbanization by generating digital divides, cyber risks, and negative externalities that can undermine urban residents' quality of life and well-being (Scheerder et al. 2017; Song et al. 2020). Therefore, it is crucial to adopt appropriate policies and strategies that can harness the potential of ICT for positive urbanization while mitigating its possible drawbacks.

Although the rational use of ICT is crucial for all countries, amplifying the favorable impacts of ICT is particularly urgent in developing countries (Haftu 2019). China is an emerging country. In the process of urbanization, it has both similarities and uniqueness with developed countries. China's rapid urbanization is accompanied by significant socio-economic benefits and a series of problems, such as the widening gap between rich and poor and severe environmental issues (Lin et al. 2016; Wang et al. 2022). Since 2009, China's new-type urbanization has been proposed intensively, referring to transforming rural areas into urban ones while improving the quality and efficiency of urbanization (Shang et al. 2018). In the meantime, the Chinese government attaches great importance to developing the digital economy, focusing on economic activities that rely on digital technologies, such as e-commerce, online services, and digital platforms (Ward and Zheng 2016). ICT is an effective way for China to achieve the goals of economic transformation, social development, and enhancement of cities' competitiveness (Lin 2019).

ICT impacts a country's economic and social development significantly. In addition, due to the different primary conditions and abilities of employing ICT (Hidalgo et al. 2020), ICT in a particular region will promote or inhibit the urbanization of focal and surrounding areas. It is necessary to recognize ICT's geographical proximity and spatial correlation (Pick et al. 2015). Only by considering the spatial factors can the analysis accurately reflect and clarify the impacts of ICT on urbanization in different regions.

The study investigated the effects of ICT on urbanization, focusing on China as a case study. A sample of 31 provincial cities in China was selected, and data on ICT and urbanization indicators from 2012 to 2021 were gathered to establish a spatial panel model. By analyzing the spatial spillover effects of ICT on demographic, spatial, and economic urbanization, the study contributes to provide valuable insights for policymakers regarding the diverse paths of development across different regions. By clearly defining the essential elements of both ICT and urbanization, the study also reveals their complex interactions and conducts a thorough evaluation of the potential advantages and disadvantages associated with ICT. The comprehensive analysis in this study enhances the understanding of the intricate relationship between ICT and urbanization, serving as a vital resource for informed decision-making and strategic planning in urban development.

The rest of the study is structured as follows. Section "Literature review" reviews the literature on ICT and urbanization and describes a research framework. Section "Data and methods" presents the indicator and data while introduces the spatial econometric method. Section "Results" and Section "Discussion" report and discuss the results, respectively. Section "Conclusions" concludes and offers suggestions and avenues for future study.

Literature review

Information and communication technology (ICT). ICT represents a comprehensive technological paradigm encompassing digital devices, networked systems, software solutions, and associated services that enable the access, creation, storage, processing, and dissemination of information. As a transformative force in modern society, ICT fundamentally reconfigures spatial-temporal constraints through three distinctive characteristics: (1) facilitating real-time communication and collaborative workflows across geographical boundaries, cultural contexts, and time zones (Arranz-López and Soria-Lara 2022); (2) empowering knowledge acquisition, creative innovation, and complex problem-solving through unprecedented access to global information resources (Ndubuisi et al. 2022); and (3) generating multidimensional impacts on regional development characterized by simultaneous digital dividends and persistent digital divides (Pradhan et al. 2021; Sawng et al. 2021; Szeles 2018).

The emergence of ICT is propelled by technological advancements that demand continuous innovation capabilities and substantial resource investments (Kurniawati 2021). Its effective deployment requires ongoing dissemination and diffusion processes, underpinned by three foundational pillars: infrastructure as the material substrate, environmental factors as operational enablers, and application maturity as the developmental benchmark (Acheampong et al. 2022; Nchake and Shuaibu 2022). Specifically, infrastructure constitutes the physical foundation enabling ICT implementation. Environmental factors encompass policy frameworks, institutional support, and cultural readiness. Application level reflects technological sophistication and adoption depth.

These interdependent components collectively determine ICT to generate sustainable socioeconomic impacts while navigating the inherent tensions between technological empowerment and inequality reinforcement. Figure 1 illustrates the connotation and characteristics of ICT, as well as the correlation between ICT measurement and its underlying meanings.

Urbanization. Urbanization represents a multidimensional process characterized by population concentration, spatial expansion of built environments, and economic structural transformation (Xing et al. 2021), serving as both a driver and consequence of industrialization and modernization (Wang et al. 2021d). Since the 1970s, global urbanization has accelerated remarkably, particularly in developing economies where China's transformation stands as a paradigmatic case (Yuan et al. 2020). Official statistics reveal China's urbanization rate reached 67% by 2024, accompanied by significant improvements in urban spatial

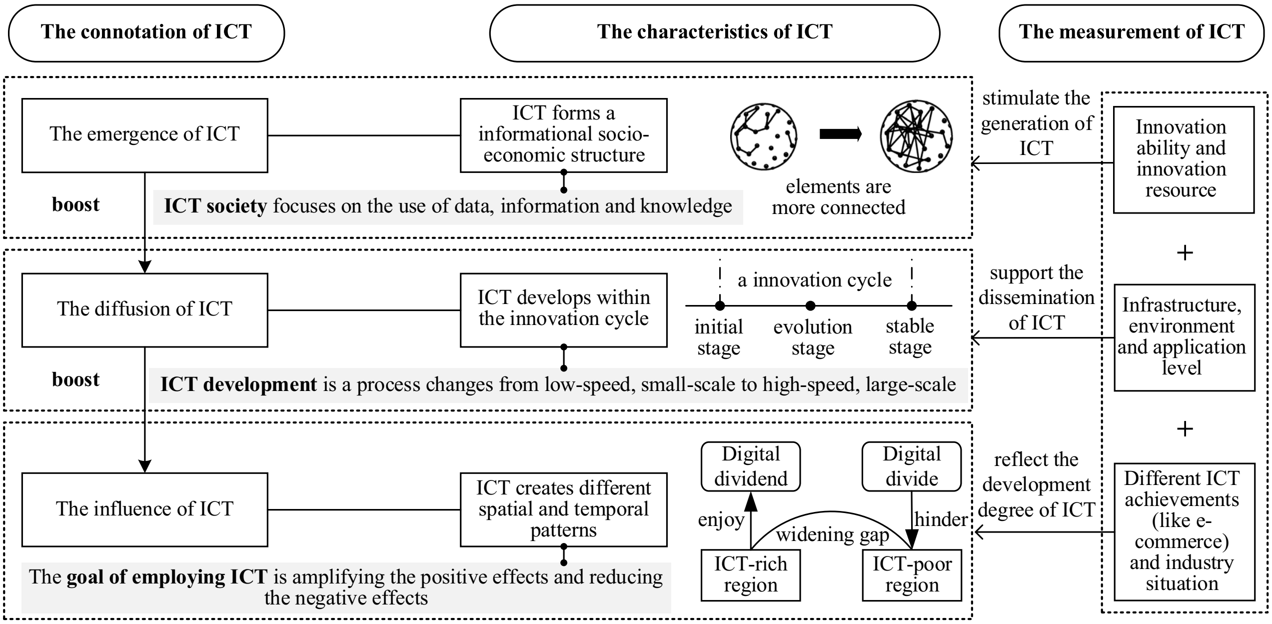

Fig. 1 The concept and feature of ICT.

configurations, economic productivity, quality of life, and resource utilization efficiency (Zhong and Chen, 2022).

Contemporary scholarship conceptualizes urbanization through three dimensions (Liu et al. 2018; Wang et al. 2014):

Demographic urbanization. The core mechanism manifesting as rural-urban migration dynamics, this process drives urban population growth and fundamentally reshapes settlement patterns (Zhou et al. 2018). As the primary engine of urban expansion, it reflects systemic transformations in employment structures and social mobility.

Spatial urbanization. Serving as the physical substrate, this dimension encompasses the strategic aggregation of built environments and infrastructure networks that support concentrated human activities (Yang et al. 2018). It operationalizes urbanization through land-use intensification and spatial connectivity enhancements.

Economic urbanization. This pivotal aspect focuses on industrial agglomeration and productivity gains, facilitating the transition from agrarian to advanced service-oriented economies through optimized sectoral allocations (Li et al. 2017).

The Chinese urbanization model exhibits a synergistic advancement across various dimensions, as indicated by the simultaneous increases in urban population proportions, the area of constructed land, and the contribution of non-agricultural GDP. This threefold framework highlights urbanization as both a result of development and a driving force for sustainable urban transformation.

The complex impacts of ICT on urbanization. Technological innovation, particularly ICT, serves as both a catalyst and an enabler of contemporary urban development through complex bidirectional mechanisms. The emergence, diffusion and influence of ICT affect urbanization at multiple levels, shaped by both constructive and disruptive forces that operate concurrently (Table 1).

The research framework. Existing research confirms the dynamic and complex interplay between ICT development and urbanization processes. While the multidimensional nature of this relationship is acknowledged, limited scholarship has systematically investigated the spatial mechanisms through which ICT affects demographic, spatial, and economic urbanization (Cheng et al. 2021). This study presents two key contributions based on a research framework: (1) the development of an analytical framework that categorizes the dual impacts of ICT across various dimensions of urbanization, (2) the identification of spatial spillover effects associated with ICT-driven urbanization, and the examination of how ICT influences urbanization through spatial effects (Fig. 2). The framework highlights critical aspects of ICT while also addressing the tripartite structure of urbanization. Spatial econometric models reveal considerable variability, suggesting that local improvements in ICT not only reshape urban development within regions but also influence neighboring areas through technological spillovers, policy imitation and externalities (Wang et al. 2021b). This spatial interdependence raises crucial questions regarding the consistency of ICT effects across regions, the dynamics of the digital divide, and the potential for coordinated development.

Data and methods

Data source and indicators of ICT and urbanization. The study sample comprises 31 provincial Chinese cities. The panel data (2012–2021) obtained from the *China Statistical Yearbook* and *China Statistical Yearbook of Science and Technology* is treated as fundamental data, and the selected variables are shown in Table 2. The process of selecting indicators adheres to three methodological principles. Firstly, a criteria-driven approach is utilized, emphasizing metrics that have gained academic recognition and empirical validity in the existing literature. Secondly, through a comparative analysis of measurement frameworks, indicators that effectively encapsulate the complex interactions between ICT development and urban transformation processes are identified. Lastly, a strong emphasis is placed on choosing variables that are backed by standardized measurement protocols and publicly accessible data sources, thereby ensuring methodological rigor in

Table 1 The dual impacts of ICT on urbanization.

Impacts of ICT on urbanization	Positive impacts	Negative impacts
Demographic urbanization	*Skill Premium Enhancement*: Creates demand for high-skilled workers while generating new employment sectors, thereby accelerating labor mobility (Qi et al. 2019).	*Digital Exclusion*: Perpetuates socioeconomic disparities through unequal technology access, limiting upward mobility for digitally marginalized populations (Tewathia et al. 2020).
Spatial urbanization	*Planning Optimization*: Enables data-driven urban design for sustainable form and functional organization (Bibri and Krogstie, 2017).	*Spatial Disruption*: Exacerbates regional disparities through uneven digital infrastructure distribution (Pick and Nishida 2015), while virtual space proliferation induces physical space redundancy (Ioannides et al. 2008).
Economic urbanization	*Productivity Gains*: Reduces transaction costs and enables new economic models through enhanced information flows (Kallal et al. 2021; Palvia et al. 2018).	*Paradoxical Limitations*: Introduces productivity paradoxes and information asymmetries that constrain economic performance (Cardona et al. 2013).

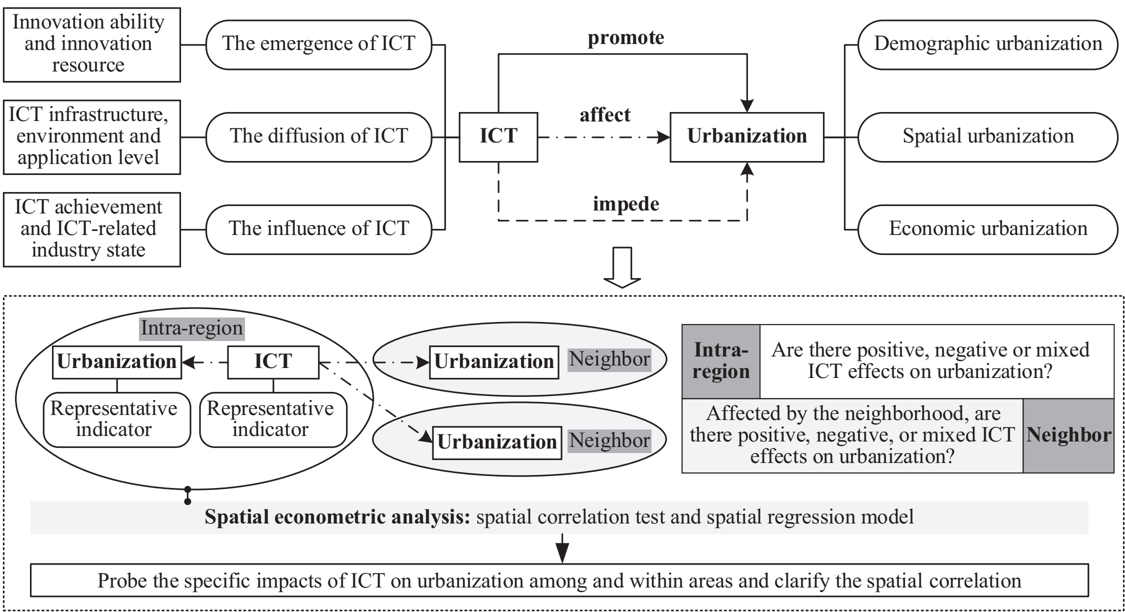

Fig. 2 The research framework.

data collection, comparative analysis, and the reproducibility of results.

Spatial econometric analysis. The working process for conducting spatial econometric analysis is illustrated in Fig. 3. The main steps involve a spatial correlation test followed by the evaluation and set of a spatial econometric model.

Spatial correlation test. The Moran's I index is used to detect the spatial correlation (Anselin 1995); the formula is expressed as follows:

$$Moran's\, I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \quad (1)$$

where X_i and X_j represent the observation values of the dependent variables in region i and region j, respectively. $\bar{X}$ is the mean value of X. W_{ij} is the spatial weight matrix. In this study, the distance-based spatial weight matrix was employed, with the threshold distance established as the minimum distance derived from the centroids of each region. n denotes the number of spatial units indexed by i and j ($n = 31$). $S^2 = \frac{1}{n}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2$.

The values of Moran's I index range from −1 to 1. Moran's I > 0 implies a positive spatial correlation. Conversely, Moran's I < 0 means negative spatial correlation. When Moran's I = 0, there is no spatial correlation. The larger the absolute value of the Moran's I index, the stronger the spatial correlation. Table 3 presents the Moran's I index for demographic, spatial, and economic urbanization from 2012 to 2021. The data indicates that Moran's I index is significantly positive at 1% for all years. It suggests that the spatial distribution of urbanization development across various regions in China is not entirely random; rather, it exhibits the existence of spatial correlation. Specifically, regions with high levels of urbanization development tend to be located near other high-level areas, while regions with low levels of urbanization development are clustered together. Consequently, it can be inferred that there is spatial autocorrelation among the dependent variables. Neglecting this relationship when assessing the impact of independent variables may lead to inaccuracies in model design and diminish the reliability of the results. Therefore, it is essential to incorporate spatial measurements into the analysis.

Model test and set. Spatial econometric models can be seen as an extension of traditional regression models that describe interactions between multiple regions by adding spatial effects to improve the accuracy of results. A change in any object associated with an explanatory variable affects the region and potentially all other regions. There are three main types of spatial econometric models (Elhorst 2011), namely the spatial

Table 2 The qualitative descriptions of selected variables.

Variable (unit)	Type	Symbol	Interpretation
The effects of ICT on demographic urbanization			
Urban population (%)	De	pop[a]	The proportion of the urban population in the total population. It represents demographic urbanization.
Science popularization funds (yuan/person)	Inde	sci[a]	The annual science popularization fundraising per capita. It represents innovation ability and innovation resource.
Internet port (port/10,000 persons)	Inde	ict[a]	The number of internet broadband access ports per 10,000 persons. It represents ICT infrastructure.
Salary level (yuan/person)	Inde	wage[a]	The average salary of information service practitioners. It represents ICT environment.
Internet use (household/10,000 persons)	Inde	int[a]	The internet broadband access per 10,000 users. It represents ICT application level.
E-commerce (enterprise/10,000 persons)	Inde	ecom	The number of businesses with e-commerce transactions per 10,000 persons. It represents ICT achievement.
Express delivery business (yuan/person)	Inde	expr[a]	The income from the express delivery business per capita. It represents ICT-related industry state.
population density (person/sq.km)	Con	den[a]	The number of urban populations per unit area.
Financial expenditure (yuan/person)	Con	budg[a]	The local general public budget expenditure per capita.
Higher education (person)	Con	edu[a]	The average number of students enrolled in higher education per 100,000 persons.
Consumption level (yuan/person)	Con	expe[a]	The consumption expenditure of urban residents per capita.
The effects of ICT on spatial urbanization (The six independent variables related to ICT remain unchanged from the previous discussion)			
Built-up area (sq.m/person)	De	spac[a]	The built-up area per capita. It represents spatial urbanization.
Industry structure (%)	Con	ind[a]	The added value of the tertiary industry accounts for the proportion of GDP.
Financial pressure (-)	Con	fin[a]	The ratio of local general public budget expenditure to revenue.
The effects of ICT on economic urbanization (The six independent variables related to ICT remain unchanged from the previous discussion)			
GDP (yuan/person)	De	econ[a]	The GDP per capita. It represents economic urbanization.
Population size (10,000 persons)	Con	tot[a]	The total population at the end of the year.
Industry structure (%)	Con	ind[a]	The added value of the tertiary industry accounts for the proportion of GDP.

Inde, De, and Con represent the independent variable, dependent variable, and control variable. GDP stands for gross domestic production.
[a]Indicates that the empirical model includes the variable as a natural logarithm.

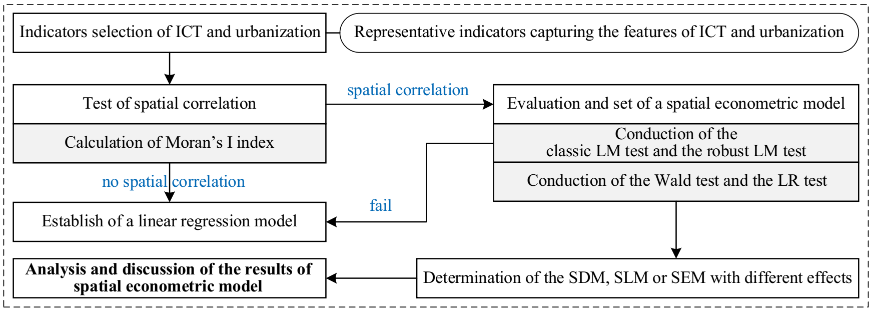

Fig. 3 Working process of spatial econometric analysis.

Table 3 The spatial correlation of demographic, spatial and economic urbanization, 2012–2021.

Demographic urbanization			**Spatial urbanization**			**Economic urbanization**		
Year	**Moran's I**	***z*-value**	**Year**	**Moran's I**	***z*-value**	**Year**	**Moran's I**	***z*-value**
2012	0.238***	3.300	2012	0.246***	3.667	2012	0.270***	3.802
2013	0.247***	3.411	2013	0.235***	3.551	2013	0.257***	3.627
2014	0.251***	3.460	2014	0.218***	3.341	2014	0.232***	3.315
2015	0.251***	3.470	2015	0.213***	3.298	2015	0.217***	3.124
2016	0.266***	3.654	2016	0.227***	3.464	2016	0.197***	2.911
2017	0.251***	3.470	2017	0.204***	3.163	2017	0.192***	2.859
2018	0.234***	3.285	2018	0.168***	2.674	2018	0.189***	2.806
2019	0.260***	3.645	2019	0.167***	2.669	2019	0.173***	2.582
2020	0.227***	3.216	2020	0.251***	3.702	2020	0.175***	2.690
2021	0.233***	3.306	2021	0.233***	3.503	2021	0.185***	2.805

***$p < 0.01$.

Table 4 Results of non-spatial panel data models.

Determinant	Pooled OLS	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects
LM spatial lag	21.992***	63.924***	48.537***	64.943***
Robust LM spatial lag	1.504	6.496**	25.263***	14.323***
LM spatial error	77.037***	72.265***	23.328***	53.390***
Robust LM spatial error	56.550***	14.836***	0.054	2.770*

***p < 0.01; **p < 0.05; *p < 0.10.

Table 5 Results of the diagnostic tests.

Determinant	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects
Wald test spatial lag	61.043***	61.844***	58.834***
LR test spatial lag	60.846***	57.534***	54.103***
Wald test spatial error	34.410***	72.818***	49.453***
LR test spatial error	36.355***	61.710***	45.765***

***p < 0.01.

lag model (SLM), the spatial error model (SEM), and the spatial Durbin model (SDM).

The SDM is a benchmark model (Anselin 1988) that considers both the spatial correlation of the independent and dependent variables. It is written as follows:

$$Y = \rho WY + \beta X + \theta WX + \varepsilon \quad (2)$$

where Y is the dependent variable, X is the independent variable, WY is the vector of the spatial lag dependent variable and WX is the vector of the spatial lag independent variable, W is the spatial weight matrix, ρ is the spatial autoregressive coefficient that measures the spatial correlation of dependent variables and θ is the spatial regression coefficient that measures the spatial correlation of independent variables, β is the coefficient of independent variable, and ε is the random error term.

Model tests were conducted orderly to select an appropriate spatial econometric model. The analysis of the effects of ICT on economic urbanization was set as an example to illustrate the specific process. First, the non-spatial panel data model was introduced for testing. Then, the Lagrange Multiplier (LM) test (Anselin et al. 2008) and robust LM test (Elhorst 2015) were employed to determine whether the null hypothesis of the non-spatial panel model was rejected. It is necessary to use the spatial econometric model for the next test based on the rejection of the non-spatial panel model.

Table 4 presents the results of four models: a pooled ordinary least squares (OLS) model, a spatial fixed effects model, a time-period fixed effects model, and a spatial and time-period fixed effects model.

When applying the LM test, the spatial lag and spatial error test results were significant at the 1% level for the four models. The robust LM test rejected the null hypotheses of no spatial lag effect and no spatial error effect for the spatial and double fixed effects models. The pooled OLS model did not pass the spatial lag test, and the time-period fixed effects model failed the spatial error test.

Overall, the values of p for most tests were <0.1, suggesting the need to consider spatial correlations among the provinces. The results were consistent with the spatial correlation test.

Whether the SDM, SLM, or SEM is ultimately used requires more tests. The most suitable model can be decided by performing the Wald test and the likelihood ratio (LR) test. Typically, the modeling process starts with the SDM, and under specific criteria, the SDM can be simplified to the SLM or the SEM. If the null hypothesis H_0: $\theta = 0$ is rejected, the SDM is simplified to the SLM. If the null hypothesis H_0: $\theta + \rho\beta = 0$ is rejected, the SDM is simplified to the SEM. If both null hypotheses are rejected, it proves that the SDM is selected to describe the data.

Table 5 displays that the results were significant at the 1% level, suggesting that the SLM and the SEM should be rejected in favor of the SDM.

The sample selected in the study is 31 provinces in China, which are spatiotemporal data covering adjacent spatial units in a continuous study area, and the fixed-effect model is a better choice for such full-sample data (Elhorst 2014). The LR test[1] was then conducted to determine which effect should be selected for the SDM. It could be seen from the results that the final model is the SDM with spatial fixed effects.

The identical modeling process was applied to evaluate the spatial econometric model examining the effects of ICT on demographic and spatial urbanization. The tests set the model involving demographic and spatial urbanization as the SDM with spatial and time-period fixed effects.

Results

Spatial econometric regression results of the effects of ICT on demographic urbanization. Among the core independent variables reported in Table 6, the effects of internet port (ict), salary level (wage), and internet use (int) were found to be positive, significantly contributing to the demographic urbanization of the focal area. The coefficients of salary level (wage) and internet use (int) were notably positive at the 1% significance level, indicating the pronounced impact of ICT. Additionally, the spatial spillover effects of salary level in the information service industry (wage) from adjacent regions were significantly positive. Conversely, the spatial spillover effects of internet-related indicators (ict and int) were found to be insignificant. This suggests that the ICT infrastructure and its application in surrounding areas have a limited influence on the demographic urbanization of the central area. Nevertheless, the overall advancement of the ICT environment in neighboring regions can enhance the demographic urbanization of the focal region. This is attributed to the externalities generated by the ICT sector, which allow the region to benefit from the technological advancements and industrial growth occurring in adjacent areas. As industrial efficiency improves, the urbanization rate of the population in both the focal and neighboring regions has experienced an overall increase.

Table 6 Estimation results of the SDM regarding the effects of ICT on demographic urbanization.

Determinant	Coefficient	*t*-value	Determinant	Coefficient	*t*-value
sci	−0.0004	−0.0924	W*sci	−0.0119	−1.0972
ict	0.0029	0.2157	W*ict	0.0047	0.1331
wage	0.0780***	4.5291	W*wage	0.0647*	1.8321
int	0.0972***	7.3044	W*int	0.0299	0.7489
ecom	−0.0225***	−3.1437	W*ecom	0.0317*	1.7382
expr	−0.0170**	−2.0465	W*expr	−0.0011	−0.0475
den	−0.0312***	−3.2545	W*den	−0.0668***	−2.8750
budg	0.0310	1.5214	W*budg	−0.1893***	−3.3438
edu	0.1545***	6.5545	W*edu	0.0185	0.3993
expe	0.0851***	2.6906	W*expe	−0.0907	−1.0796
ρ			0.0650		

***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

Table 7 Estimation results of the SDM regarding the effects of ICT on spatial urbanization.

Determinant	Coefficient	*t*-value	Determinant	Coefficient	*t*-value
sci	0.0029	0.2846	W*sci	−0.0160	−0.6656
ict	0.0594*	1.8764	W*ict	−0.1924**	−2.3129
wage	−0.0643*	−1.7770	W*wage	−0.0116	−0.1541
int	0.0778**	2.4890	W*int	0.2635***	3.0043
ecom	0.0110	0.7387	W*ecom	−0.0815**	−2.0414
expr	0.1378***	7.3193	W*expr	−0.0270	−0.6649
ind	0.0492	0.8821	W*ind	0.0349	0.2389
fin	0.0979*	1.9996	W*fin	0.0044	0.0447
ρ			−0.1050		

***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

The science popularization funds (sci), e-commerce (ecom), and express delivery business (expr) had adversely affected demographic urbanization. This unexpected result indicates that the development of ICT in the targeted region is quite intricate, complicating the accurate assessment of its short-term effectiveness. As a result, there is a delay in the positive impacts of ICT on demographic urbanization in the area of focus (Vu et al. 2020). Conversely, these factors in neighboring regions did not demonstrate significant negative spatial spillover effects on the demographic urbanization of the central area. It appears that adjacent regions inevitably siphon off some developmental resources from the central region, heightening its vulnerability to ICT advancements in surrounding areas (Wu et al. 2021). This is evidenced by the rise of ICT innovation resources (sci) and ICT-related industry state (expr) in neighboring areas, which create additional job opportunities and improve the working environment, thereby attracting migrants and reducing the urbanization rate in the central region. Furthermore, there are ICT advancements that promote demographic urbanization across regions. In this empirical analysis, the use of e-commerce (ecom) in surrounding areas, which transcends both temporal and spatial constraints, mitigated unnecessary population movement and significantly enhanced the urban population proportion in the focal area (Zhang et al. 2022c).

In terms of control variables, fiscal expenditure (budg), higher education (edu), and consumption level (expe) had promoting effects on demographic urbanization, of which the role of higher education was the most significant, followed by the consumption level. It shows that improving the quality of the population and residents' consumption level has vital impacts on demographic urbanization. Conversely, a 1% rise in urban population density (den) corresponded to a reduction of 0.0312% in the urbanization rate of the population. Increased urban population density correlates with a heightened demand for resources. The mismatch between demand and supply will hinder the further development of demographic urbanization. For spatial spillover effects, the increase in urban population density (den) and fiscal expenditure (budg) in neighboring areas significantly inhibited the growth of the urban population in the central location. The high level of urbanization in surrounding regions powerfully attracts or even grabs the better resources of the focal area. As a result, the population flows to adjacent regions, combined with the decline of the central region's urbanization level.

In summary, indicators associated with the dissemination of ICT exert the most significant and pronounced influence on the demographic urbanization within the region. In contrast, indicators related to the emergence and influence of ICT have a relatively minor effect on enhancing the urbanization rate. Consequently, when promoting demographic urbanization through ICT in the region, it is essential to prioritize factors such as ICT infrastructure, environment, and application level.

Furthermore, the implementation of certain ICT variables in neighboring areas poses challenges to the demographic urbanization in the central region. This resistance is particularly evident in areas where ICT development has reached an advanced stage, resulting in resource exploitation in less developed ICT regions. The spillover effects of ICT benefits to the region are minimal, exacerbating the digital divide and intensifying the existing disparities in development, which in turn hampers urbanization efforts. However, enhancing the ICT industry and leveraging the positive impacts of ICT can help narrow the developmental gap between regions.

Spatial econometric regression results of the effects of ICT on spatial urbanization. The effects of ICT on spatial urbanization are reported in Table 7. Among all the variables, only the internet-related indicators (ict and int) and express delivery business (expr) had obvious positive impacts on expanding the

Table 8 Estimation results of the SDM regarding the effects of ICT on economic urbanization.

Determinant	Coefficient	*t*-value	Determinant	Coefficient	*t*-value
sci	−0.0085	−0.6604	W*sci	−0.0641**	−2.1964
ict	−0.0146	−0.4002	W*ict	−0.0927*	−1.8042
wage	0.1396***	3.3699	W*wage	0.0690	0.9860
int	0.1611***	4.2447	W*int	−0.0658	−1.0234
ecom	0.1300***	7.1972	W*ecom	−0.1937***	−5.1058
expr	0.1005***	3.9441	W*expr	−0.0284	−0.6645
tot	−0.0433	−0.2792	W*tot	1.1039***	3.4770
ind	−0.5465***	−8.1648	W*ind	0.3907***	2.7603
ρ			0.594***		

***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

built-up area in the focal region. The swift proliferation of the internet has established technological innovation and industrial integration as key objectives for development, and the emergence of new industries expands the urban space as well as reshapes the urban form (Wang et al. 2021e). Meanwhile, the vigorous development of the express delivery business requires more convenient urban transportation. Urban space continues to expand and improve with the construction of urban infrastructure. The increase in the salary level of the information service industry (wage) had significantly negative effects on spatial urbanization, which produced results that were not in line with expectations. This is primarily due to the inherent instability in the development of emerging industries, coupled with the inadequate distribution of supporting infrastructure, which hinders timely urban spatial planning.

In addition, within the context of spatial spillover effects associated with ICT factors, the application of the internet (int) in adjacent regions demonstrated a significantly positive influence on the spatial urbanization of the focal area, with an impact magnitude of 0.2635. This underscores the critical importance of internet proliferation and its application in the comprehensive and rational organization of urban space. Other ICT indicators (sci, ict, wage, ecom, and expr) in adjacent regions exerted detrimental impacts on the central region's spatial urbanization. It can be inferred that the noticeable siphoning effects among regions contribute to uneven regional development, resulting in the persistence of the digital divide (Rath 2016).

For the control variables, financial pressure (fin) and industry structure (ind) had favorable effects on spatial urbanization. As urban areas expand, the development of infrastructure and public service facilities necessitates significant capital investment. This demand poses challenges to government fiscal expenditures, and the resulting financial pressures highlight the government's enthusiastic commitment to increasing the built environment. Moreover, the rationalization of industrial structures will also promote the expansion of urban space. Regarding the spatial spillover effects, the increase in financial pressure and the change of industrial structure in surrounding areas positively affected the focal area's spatial urbanization.

The analysis of the effects of ICT on spatial urbanization reveals that the expansion of urban areas primarily reflects governmental actions within administrative boundaries. The spatial interdependence with neighboring regions is notably limited, and the impact of ICT on the growth of built-up areas is also minimal. It is evident that not all regions reap the benefits of ICT; rather, many exhibit varied and delayed responses to external ICT stimuli. This underscores the necessity for policymakers to assess the diverse effects of ICT thoroughly and accurately when developing appropriate strategies.

Spatial econometric regression results of the effects of ICT on economic urbanization. According to the results presented in Table 8, the spatial parameter ρ was significantly positive at the 1% level, confirming a significant spatial correlation between China's regional economic growth. That is to say, the economic development of neighboring regions plays an essential role in promoting the focal region's economy.

Most ICT indicators positively affected economic urbanization. Among them, the salary level (wage), internet use (int), e-commerce (ecom), and express delivery business (expr) had prominent effects on the increase of GDP per capita. The four coefficients were 0.1396, 0.1611, 0.1300, and 0.1005, respectively, which were all significant at the 1% level. In general, it is believed that the development of ICT has improved traditional industries from the aspects of industrial innovation, integration, transformation, and upgrading (Zhang et al. 2022b). The transformation of economic structures, along with the expansion of scale and enhancements in efficiency, has significantly invigorated the economy, facilitating a seamless process of economic urbanization. Among the ICT indicators that positively affect economic development, internet use, which represents the application level of ICT, has the most significant effect. This proves the essential position of the internet in economic urbanization (Nabi et al. 2023).

In contrast, for the spatial spillover effects of ICT in surrounding areas on the focal area's economic urbanization, most indicators (sci, ict, int, ecom, and expr) had negative impacts. The adverse effects of e-commerce (ecom) were most pronounced: a 1% increase in ecom in neighboring regions will limit the central region's economic development by 0.1937%. The results highlight the regional development imbalance, further exacerbated by the digital divide. While ICT stimulates economic growth in the focal area, neighboring areas are also leveraging ICT to enhance their economies and reap the benefits of digital dividend. Consequently, the surrounding regions tend to attract talent, capital, technology, and other resources from the focal region, leading to a concentration of resources in these adjacent areas, which in turn hampers the economic development of the focal region (Wang et al. 2021c).

Lastly, the effects of control variables were analyzed. Population size (tot) and industry structure (ind) impeded economic urbanization in this empirical analysis. It indicates that the industrial development environment is more complex in practice, and the positive impacts of optimizing industry structure may be delayed. Additionally, considering that the development of high-end industries has higher requirements for labor quality rather than quantity, the increase in employment difficulty also causes the reduction of employment opportunities in the short term, which will hinder the promotion of economic urbanization. The

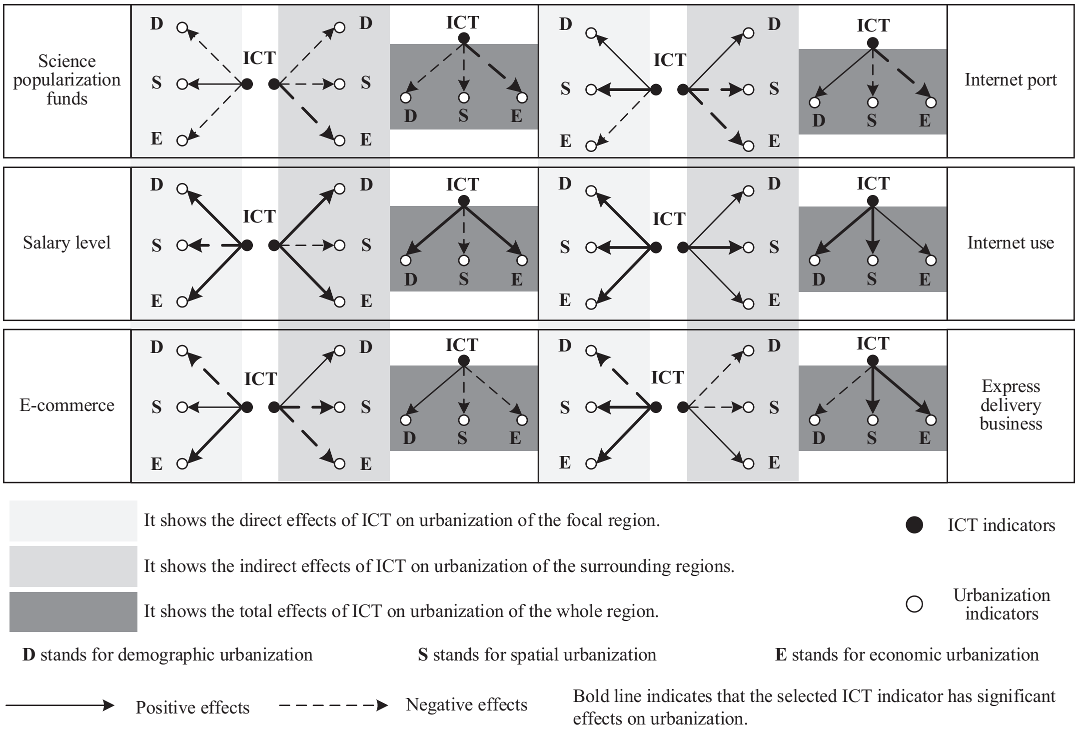

Fig. 4 The analytical path diagram of the effects of ICT on urbanization.

rise in population (tot) and the change of industrial structure (ind) in neighboring areas boosted the central area's economic growth. Probably, there is a competitive relationship of mutual learning and imitation between regions (Wang et al. 2021a), which has prompted surrounding areas to modify some unfavorable factors in the process of economic urbanization and seek development paths that benefit themselves. As essential catalysts for the economy, the stable structure of industry and growing population have brought positive spatial spillover effects. With a gradual improvement of production efficiency, the coordinated development of the regional economy can reach.

In conclusion, ICT plays a crucial role in fostering regional economic growth; however, its impacts are complex and require individual analysis. The presence of a digital divide has exacerbated the disparities in economic development among regions. While ICT is currently at a mature stage and positively influences the economic growth of a region, it has yet to generate a significant scale effect for adjacent areas during this growth phase. This limitation hinders the economic growth and efficiency enhancement of all regions, resulting in a lack of a strong positive correlation between ICT and the economic development.

Discussion

The effects of standard ICT indicators on various aspects of urbanization were examined from a spatial viewpoint. An analytical path diagram (Fig. 4) was constructed based on the decomposition results of the spatial effects of ICT on urbanization (Table 9) (Lesage and Pace 2009). Table 9 and Fig. 4 demonstrate that ICT indicators have influenced urbanization in both the central region and its adjacent areas. When ICT promotes urbanization in the central area and its surroundings, or when its positive effects surpass any negative repercussions, urbanization benefits from a supportive influence driven by ICT. Conversely, when urbanization is impeded, it faces a constraining force shaped by ICT. The study contends that not all regions can swiftly reap the benefits of ICT, as differing stages of development lead to varying perceptions of its advantages. This capability gap not only creates but also exacerbates the existing inequalities and gives rise to new challenges.

The diverse influences of ICT, especially the negative impacts of ICT highlight the possibility of a digital divide across different regions. Despite the adverse effects of ICT stemming from delays and limitations in technical efficiency, the primary contributor to these negative impacts is the digital divide (Philip and Williams 2019). The digital divide refers to the disparities in access to technologies that enhance quality of life, as well as variations in the capacity to obtain information and resources (Reddick et al. 2020). It also encompasses the potential for technology to either mitigate or worsen pre-existing inequalities. This divide is a significant factor underlying various social issues and phenomena, such as digital inequality, and represents a multifaceted challenge with numerous levels and dimensions (Scheerder et al. 2017). Tackling the issue of the digital divide is crucial for the future.

In addition, it can be concluded from Table 9 and Fig. 4 that ICT plays a crucial role in economic development, and the key path of ICT-based urbanization can be derived from the economic dimension. Meanwhile, factors representing the ICT environment, application level, and achievement have increasingly important impacts on urbanization, and such ICT indicators need to serve as catalysts for positive change in the future.

According to the analytical path diagram of the effects of ICT on urbanization, the specific path in different regions under the impact of spatial effects can be further displayed (Fig. 5). Due to the compensatory effect, imitation effect, industrial externality, subsidy effect, and Matthew effect (Tewathia et al. 2020; Wang et al. 2021a; Wang et al. 2021b; Zeng 2019), ICT exerts different spillover effects on urbanization. The varied effects of ICT on urbanization are underscored, emphasizing the need to enhance its positive impacts. Meanwhile, tackling the adverse outcomes of ICT poses a considerable and pressing challenge for regional development.

Table 9 Spatial effects decomposition.

Determinant	Direct effect		Indirect effect		Total effect	
	Coefficient	*t*-value	Coefficient	*t*-value	Coefficient	*t*-value
The effects of ICT on demographic urbanization						
sci	−0.001	−0.176	−0.013	−1.124	−0.014	−1.051
ict	0.004	0.284	0.004	0.089	0.008	0.171
wage	0.079***	4.600	0.075*	1.960	0.154***	3.281
int	0.097***	7.456	0.040	0.961	0.137***	3.140
ecom	−0.022***	−3.093	0.033	1.603	0.010	0.454
expr	−0.017**	−2.020	−0.003	−0.137	−0.020	−0.765
den	−0.032***	−3.264	−0.073**	−2.827	−0.105***	−3.425
budg	0.028	1.331	−0.202***	−3.146	−0.175**	−2.485
edu	0.156***	6.391	0.032	0.670	0.188***	3.403
expe	0.084**	2.692	−0.091	−1.000	−0.007	−0.074
The effects of ICT on spatial urbanization						
sci	0.003	0.268	−0.016	−0.700	−0.013	−0.526
ict	0.062*	1.894	−0.188**	−2.378	−0.126	−1.454
wage	−0.063*	−1.791	−0.004	−0.050	−0.066	−0.813
int	0.074**	2.428	0.238***	2.881	0.3128***	3.733
ecom	0.012	0.826	−0.075**	−1.958	−0.062	−1.494
expr	0.138***	7.401	−0.040	−1.092	0.0988***	2.943
ind	0.048	0.851	0.030	0.217	0.078	0.508
fin	0.098*	1.962	−0.005	−0.052	0.093	1.061
The effects of ICT on economic urbanization						
sci	−0.017	−1.159	−0.163**	−2.170	−0.180**	−2.132
ict	−0.028	−0.777	−0.238**	−2.321	−0.266**	−2.449
wage	0.162***	3.684	0.355**	2.033	0.517***	2.644
int	0.165***	4.468	0.077	0.600	0.242	1.790
ecom	0.115***	5.943	−0.270***	−2.799	−0.155	−1.469
expr	0.102***	4.067	0.070	0.774	0.172*	1.811
tot	0.093	0.611	2.533***	3.643	2.626***	3.768
ind	−0.536***	−7.599	0.163	0.490	−0.374	−1.024

***$p < 0.01$; **$p < 0.05$; *$p < 0.10$.

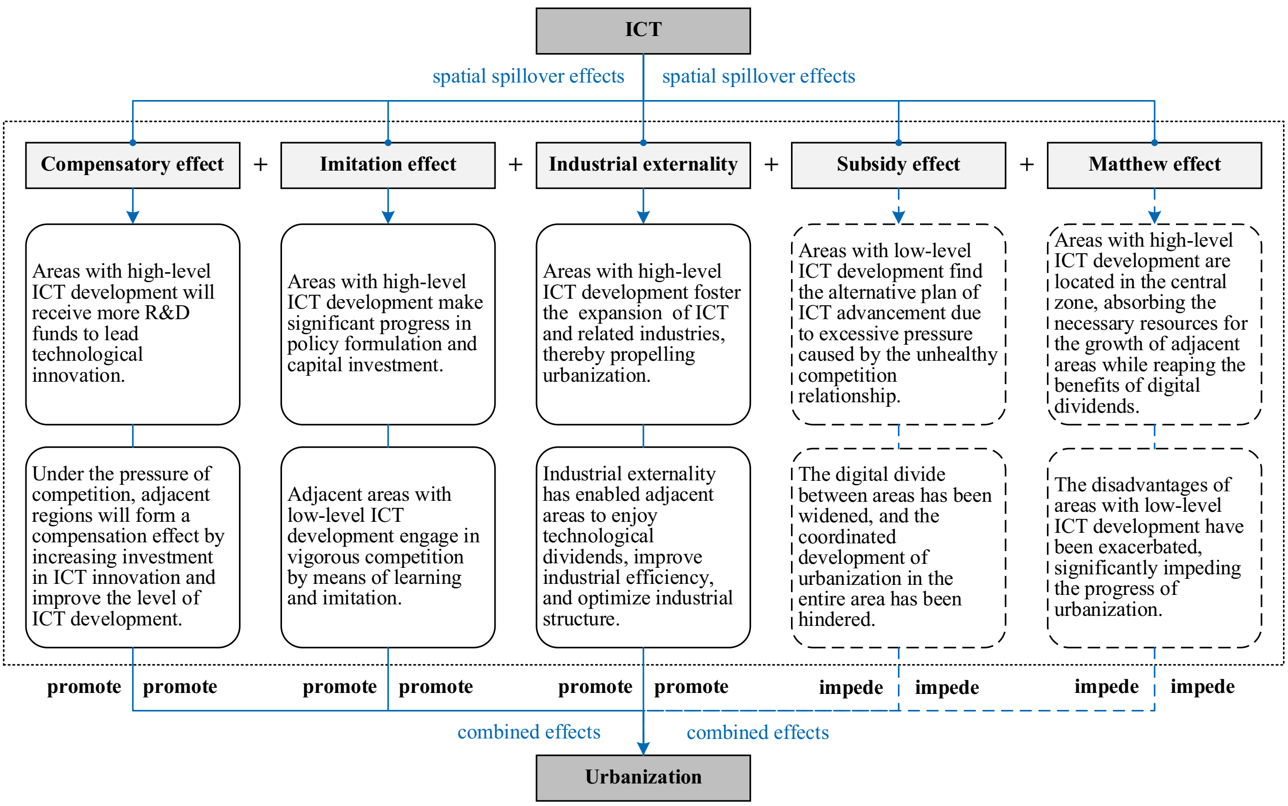

Fig. 5 The path analysis under the impact of spatial effects of ICT on urbanization.

To enhance the beneficial impacts and mitigate the adverse effects of ICT, the study provides targeted recommendations in three key areas for most regions: promoting research and development in ICT technologies, bridging the digital divide, and fostering a robust industrial ecosystem. These three dimensions offer suggestions for ICT-driven urbanization development, focusing on the supply side, demand side, and environmental considerations.

The establishment and strengthening of an ICT-based innovation system is paramount in harnessing the transformative power of information technology, data, and digital platforms to facilitate urbanization effectively. The core of ICT development is rooted in technological advancements and breakthroughs that serve as catalysts for urban growth. By creating a robust ICT innovation system, we can delineate research priorities that focus on essential ICTs, while intensifying development efforts in cutting-edge and critical technologies. This approach will enable the creation of unified ICT platforms and comprehensive databases, providing a technological foundation for urbanization initiatives. The rapid pace of urbanization can be significantly accelerated by leveraging the advancements fostered by ICT, ultimately leading to more efficient urban environments that can adapt to the needs of growing populations.

In addition to establishing an innovation system, it is crucial to fully utilize and optimize the capabilities of ICT-based infrastructure services to create a comprehensive public service system. This system is essential for promoting high-quality and efficient urbanization. By employing ICT to enhance the equitable distribution of basic public services, we can effectively alleviate disparities that arise from the digital divide. This divide often restricts access to the benefits of ICT, thereby hindering the potential for balanced urban development. Therefore, employing ICT to promote the equalization of public services and facilitate coordinated urban development is vital in bridging regional development gaps. This strategy not only improves the overall quality of urbanization but also fosters more harmonious and livable urban environments for residents, ensuring that all citizens can benefit from the advancements in technology.

Furthermore, prioritizing the development of ICT-based industries is essential for cultivating an environmentally sustainable industrial ecosystem that can directly stimulate urbanization. The integration of ICT into industrial processes enhances efficiency and productivity, which is crucial for urban growth. By fostering ICT industries, extending industrial chains, and creating collaborative, service-oriented industrial ecosystems, we can promote the integration of ICT with traditional industries. This integration is important for nurturing emerging sectors that can drive innovation and economic growth. The enhancement of overall industrial capabilities through ICT ensures that urbanization development is sustainable and environmentally conscious.

In conclusion, the comprehensive approach to leveraging ICT in urbanization encompasses the establishment of an innovation system, the optimization of public service delivery, and the prioritization of ICT-based industries. Each of these components plays a critical role in shaping the future of urban environments. By embracing the potential of ICT, we can create urban spaces that are not only technologically advanced but also equitable and sustainable. This holistic strategy will ultimately lead to the development of cities that are better equipped to meet the challenges of urbanization, ensuring a higher quality of life for all residents, and fostering a more inclusive and prosperous society.

Conclusions

The study quantitatively explores the effects of ICT on urbanization, using data on ICT and urbanization indicators from 31 provinces in China from 2012 to 2021. The development of ICT is categorized into three phases: emergence, diffusion, and influence, while urbanization is characterized by demographic, spatial, and economic dimensions. A spatial analysis is conducted, utilizing the SDM to interpret the effects of ICT on population migration, land construction, and economic growth.

The results demonstrate that ICT has both positive and negative effects on urbanization. When clarifying the complex effects of ICT, it is necessary to make a specific analysis in combination with the foundational and development environment of the region. The digital divide has aggravated the development imbalance between regions, promoting the focal area's urbanization while inhibiting the surrounding areas to a certain extent. However, with appropriate measures in place, the feedback effects are not invariably negative; due to the industrial externalities and the learning and limitation relationship between regions, the areas in the backward state will also be stimulated by neighboring areas to compensate for the development of ICT, including funds, labor, technology, etc., narrowing the existing gap and obtaining the benefits of ICT. The results also show that ICT has a substantial impact on economic urbanization, and indicators concerning ICT environment, application level, and achievement play crucial roles in urbanization. When formulating corresponding policies, these factors should be considered.

In summary, the study provides empirical evidence of the substantial spatial spillover effects of ICT across three key dimensions of urbanization. Building on these insights, future research will systematically investigate the local geographical heterogeneity of ICT's effects in relation to different urbanization patterns. The analytical framework will be specifically focused on municipal and prefecture-level urban centers, facilitating the creation of tailored policy frameworks. These targeted strategies aim to enhance ICT's pivotal role in promoting sustainable urban development through spatially differentiated implementation approaches.

Data availability

The data used in this study are publicly available and were obtained from *China Statistical Yearbook* and *China Statistical Yearbook of Science and Technology*. These datasets can be accessed through the official website of the National Bureau of Statistics (http://www.stats.gov.cn/). Additional details regarding data sources are available from the corresponding author on reasonable request.

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Note

1 Different LR tests are based on the log-likelihood values of different models.

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Author contributions

Di Wang: Conceptualization, Formal analysis, Methodology, Software, Writing—Original draft preparation. Zhaohui Sun: Methodology, Software, Visualization. Renhao Yang: Validation, Writing—Review & Editing. Qingyuan Yang: Project administration, Resources, Supervision.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This study does not involve human participants. All data used in this research were obtained from publicly accessible databases. As the data are publicly available and do not contain identifiable personal information, informed consent was not applicable.

Additional information

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