

Impact of the digital economy on high-quality urban economic development: Evidence from Chinese cities^{☆,☆☆}

Bingnan Guo^a, Yu Wang^a, Hao Zhang^a, Chunyan Liang^a, Yu Feng^a, Feng Hu^{b,*}

^a School of Humanity & Social Science, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, China

^b School of Business Administration, Zhejiang Gongshang University, Hangzhou, Zhejiang, China

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ABSTRACT

The establishment of China's big data comprehensive pilot zones has promoted the deep integration of big data and cloud computing, accelerating the development of the digital economy. Previous studies have mainly examined the impact of the digital economy from a single perspective. Thus, using data in China and employing a difference-in-differences approach, we analyzed the impact of the digital economy from the comprehensive perspective of high-quality urban economic development. The channel analysis showed that the digital economy significantly stimulates high-quality economic development through two mechanisms: improving human capital and promoting green technology innovation. Moreover, the digital economy can alleviate the crowding effect in developed areas, such as the eastern region and large cities, which provide a good foundation for high-quality economic development. Our findings offer new insights into the real impact of the digital economy on urban economic development.

1. Introduction

Since China's reforms and opening-up, its economy has made significant achievements. However, various problems, such as unreasonable industrial structure, unbalanced regional development, and insufficient innovation, are still major obstacles affecting the quality and sustainability of the country's economic development (Fan et al., 2021). In this regard, the 19th Communist Party of China (CPC) Congress Report proposed that "China's economy has shifted from high-speed growth to a stage of high-quality development," and it has become urgent to transform the mode of economic development, optimize the economic structure, and change the growth momentum (Zhou et al., 2020). Meanwhile, the contribution of traditional factors to economic growth has been gradually shrinking.

With the rapid development of information technologies, such as big data, artificial intelligence, cloud computing, and blockchain, countries around the world are facing a profound information technology revolution (Yin et al., 2019). In this regard, the digital economy has become an important engine for global economic change and a driver for China's high-quality economic development. First, units or individuals can use

big data technology to obtain valuable information and improve the quality of human capital in the process of information transfer, value addition, and multiplication (Li et al., 2022a, 2022b, 2022c, 2022d). Second, big data technology can make all types of information in the market more transparent, while enterprises can reduce the cost of green technology innovation and target innovation based on consumer information (Zhao and Xin, 2022). Thus, to achieve high-quality economic development, promoting green technology innovation and improving the quality of human capital through the digital economy has become the main trend in global development.

At this point, what is the logical connection between the digital economy and the quality of economic growth in Chinese cities? If the digital economy can drive high-quality urban economic development, then what are the theoretical mechanisms? Additionally, is there any heterogeneity in the impact of the digital economy on high-quality urban economic development? To answer these important questions, an in-depth exploration can provide a new perspective for furthering the development of the digital economy, accelerating digital development in China, and improving the quality of economic growth in Chinese cities.

Canadian author and business executive Don Tapscott first

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^{*} Corresponding author.

E-mail addresses: 200600002509@just.edu.cn (B. Guo), 202090002@stu.just.edu.cn (Y. Wang), haozhcn@just.edu.cn (H. Zhang), 192211203113@stu.just.edu.cn (C. Liang), 211111201102@stu.just.edu.cn (Y. Feng), hufeng@mail.zjgsu.edu.cn (F. Hu).

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introduced the concept of the digital economy, after which the U.S. Department of Commerce released reports on the digital economy in 1998 and 1999 (Miao, 2021). From the perspective of economic activity, the digital economy is a series of economic activities based on network information and communication technology (Pan et al., 2022). Meanwhile, from the perspective of social form, the digital economy is an economical form distinguished from the perspective of technology (Li, 2017). Specifically, it is based on digital technology and data (which are deeply integrated into all areas of society), with the purpose of promoting sustainable economic development (Pei et al., 2018). In sum, the digital economy has a broad connotation, and any economic form that uses big data to optimize the allocation of resource factors and generate advanced productivity can be classified as such.

As a new economic form following the agricultural and industrial economies, the digital economy has attracted extensive academic attention. Many scholars have studied the impact of the digital economy from the perspective of industrial upgrading (Luo et al., 2022), urban migrant integration (Zou and Deng, 2022), production efficiency (Zhang et al., 2022), corruption (Gouvea and Li, 2022), sustainable development (Luo et al., 2022), corporate innovation (Li et al., 2022a, 2022b, 2022c, 2022d), and carbon emissions (Xue et al., 2022). However, these studies have mainly focused on the role of the digital economy in economic and environmental fields from a single perspective. Meanwhile, some research has examined the logical relationship between the digital economy and high-quality development. For example, Yu and Zhou (2021) analyzed the current state of the digital economy and its development in Henan Province and found that the region's high-quality economic development is under "double circulation," while Yang et al. (2022) revealed a significant U-shaped curve relationship between platform economy and high-quality economic development, with the former contributing more to high-quality economic development in the northeastern and western regions. In a related study, Ding et al. (2022) demonstrated that the digital economy promotes high-quality economic development and has a significant positive spatial spillover effect, based on the panel data of 30 Chinese provinces from 2011 to 2019.

In sum, the existing literature on the effects of the digital economy has been relatively affluent. These results are also valuable references for our study in exploring the logical relationship between the digital economy and high-quality economic development. However, there is an essential question about how the digital economy contributes to high-quality development, since previous studies have not reached a uniform conclusion. Meanwhile, human capital and green technology innovation (as essential drivers of economic development) play an important role in upgrading the industrial structure and transforming new growth drivers. These two aspects provide strong support for promoting high-quality economic development. Therefore, the present study builds a complete framework to determine how the digital economy drives high-quality economic development. Moreover, by using Chinese cities as research objects, we explore the logical relationship between the digital economy and high-quality economic development in a more detailed spatial scale.

Specifically, this study constructs an evaluation index system of high-quality economic development at the city level from five dimensions: industrial structure, inclusive total factor productivity (TFP), technology innovation, ecological environment, and residents' living standards. It also applies the entropy method to calculate the high-quality economic development level of 283 cities in China. Furthermore, based on the establishment of big data comprehensive pilot zones, we adopt the difference-in-differences (DID) method to investigate the impact of the digital economy on high-quality urban economic development.

The main innovations of this research can be summarized as follows. First, this study uses the establishment national big data comprehensive pilot zones to assess the impact of the digital economy on high-quality urban economic development, enriching the literature in related fields. Second, this study provides a comprehensive analysis of the relationship between the digital economy and high-quality economic

development at the city level, enabling a more detailed perspective. Third, from the theoretical and empirical perspectives, this study finds that the digital economy can improve the quality of urban economic development by promoting human capital and green technology innovation. Fourth, this study evaluates the digital economy's net effect on high-quality urban economic development by using the difference-in-differences model and combining a series of robustness tests to ensure the credibility of the results.

The remainder of this study is organized as follows. Section 2 presents the policy background and theoretical analysis, while Section 3 constructs the DID model and introduces the dataset, including the digital economy and other variables. Section 4 discusses the main results, while Section 5 conducts further analyses, including mechanism and heterogeneity tests. Finally, Section 6 presents the conclusion and some policy recommendations.

2. Theoretical framework

2.1. Background

Following the Industrial Revolution, capital became the key to economic and social development, after which advanced factors of production, such as management and technology, were introduced. With the emerging digital economy, big data has become a vital driving force for China's high-quality economic development. As early as 2014, big data was mentioned in the government's work report, and in 2015, the State Council issued the "Action Outline for Promoting the Development of Big Data." In 2016, the "13th Five-Year Plan Outline" officially proposed the implementation of its national big data strategy, after which the 19th National Congress of the CPC in 2016 pointed out that it was necessary to promote the deep integration of the internet, big data, artificial intelligence, and the actual economy. In 2019, big data was mentioned in the government's work report for the sixth time. Finally, in 2020, the State Council issued the "Opinions on Building a Perfect Institutional Mechanism for the Marketization of Factors," formally identifying data as a factor of production.

Through these documents, we can see the importance of developing big data at the national level and promoting the dynamic energy of the digital economy for social development. For example, the State Council's "Action Outline for Promoting the Development of Big Data" in 2015 clearly mentioned its strategy "to promote the construction of Guizhou and other big data comprehensive pilot areas." In February 2016, the National Development and Reform Commission, the Ministry of Industry and Information Technology (MIIT), and the Cyberspace Administration of China approved the construction of big data comprehensive pilot zones in Guizhou Province, although construction started in September 2015. In October 2016, the aforementioned organizations approved the construction of a second batch of pilot zones, including Beijing, Tianjin, Hebei, Guangdong, Shanghai, Henan, Chongqing, Shenyang, and Inner Mongolia.

Overall, the development of the digital economy mainly depends on data elements and modern communication technology. Since big data comprehensive pilot zones include the "information infrastructure upgrading project," their establishment not only enhances data mining and related applications but also promotes the development of modern information and communication technology. In light of the establishment of these zones in Chinese cities, we can explore the logical relationship between the digital economy and high-quality urban economic development.

2.2. Theoretical analysis and research assumptions

Based on endogenous economic growth theory, this study constructed an analysis framework that examines how the digital economy affects high-quality urban economic development, from the perspective of human capital and green technology innovation.

First, the digital economy has accelerated human capital accumulation, thereby promoting high-quality urban economic development. In this regard, the digital economy's high permeability and value have changed traditional production methods and industrial models (Wang et al., 2022). Additionally, the development of new industries has led to a fundamental change in the demand for human capital, requiring more highly skilled workers. Hence, the change in market demand has forced the labor market to improve their skills, driving up the region's overall level of human capital (Wang and Cen, 2022). The internet and big data applications have also provided more sophisticated and convenient technical means for disseminating educational information, breaking the spatial constraints of knowledge, technology, and other information (Ferreira et al., 2019). This has optimized the labor force's skills, education, and knowledge structure, thus improving labor productivity (Viollaz, 2019).

Moreover, higher levels of human capital have become a driving force in high-quality economic development in Chinese cities (Managi et al., 2021). Meanwhile, as the level of human capital increases, it matches high-skilled physical capital with high-level labor, resulting in higher labor productivity and high-quality development of China's economy (Xu and Li, 2020). Therefore, we propose the first hypothesis.

Hypothesis 1. The digital economy can drive high-quality economic development by improving the level of human capital.

Second, the digital economy has promoted urban green technology innovation, which, in turn, has driven high-quality urban economic development. At the macro-level, the development of the digital economy can promote the agglomeration of innovation elements, such as high-end talents, high-tech enterprises, and R&D capital, thus improving the city's green technology innovation level (Ma and Zhu, 2022). At the micro-level, the main body of green technology innovation includes enterprises (Li et al., 2022a, 2022b, 2022c, 2022d). Specifically, in the digital economy, consumers tend to pursue more diverse products and green consumption concepts, forcing enterprises to carry out green technology innovation and adopt green production methods (Han et al., 2021). Meanwhile, data technology development can help reduce enterprises' costs of carrying out such innovation (Goldfarb and Tucker, 2019).

The next question is how green technology innovation can improve the quality of urban economic growth. In the high-quality economic development of Chinese cities, the importance and scarcity of resources are becoming increasingly prominent, with the environment as strategic capital for economic development. In comparison, green technology innovation can directly create economic value (Du and Li, 2019). For example, green innovation can change production processes, reduce governance costs, develop green products, and improve management efficiency. Consequently, this can significantly reduce the environmental impact of production and consumption, save production resources, and improve the market competitiveness of enterprises (Wang et al., 2021). Based on these findings, we propose the second hypothesis.

Hypothesis 2. The digital economy can drive high-quality economic development by promoting green technology innovation.

This study also constructs a conceptual model of the main variables, as shown in Fig. 1.

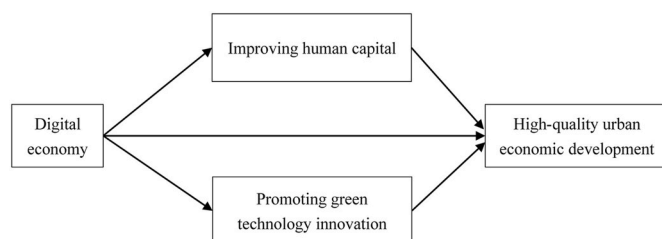


Fig. 1. The conceptual model.

3. Research design

3.1. Data and variable definitions

Our study sample consisted of 283 cities in China and their city-level data from 2005 to 2019. This data was obtained from the China City Statistics Yearbook, the China Environmental Statistics Yearbook, and the EPS database.

3.1.1. Dependent variable: high-quality economic development

To scientifically evaluate the impact of the digital economy on high-quality urban economic development, it is necessary to measure the high-quality economic development level. Based on related literature (Zhao et al., 2020; Zhou et al., 2020) and our city-level data, we constructed a comprehensive index system for measuring high-quality economic development that includes five dimensions: industrial structure, inclusive TFP, technology innovation, ecological environment, and residents' living standards. The specific index composition is listed in Table 1.

In this index system, to objectively reflect genuine changes in economic growth at the city level in China, nominal variables (e.g., the GDP and the GDP per capita) were converted into real variables, with 2004 as the base period. Per capita data was calculated from each city's total population at the end of the year. Additionally, drawing on relevant literature, industrial structure rationalization was measured using a modified Thiel index (Su and Fan, 2022), while advanced industrial structure was expressed by the ratio of the added value of the tertiary and secondary industries (Liu et al., 2021). As for the proportion of the producer service industry, it was expressed by the proportion of this industry among urban employees. The producer service industry mainly includes transportation, storage, post and telecommunications, information transmission, computer service and software, financial, leasing, commercial service, scientific research and technical service, and geological exploration. Moreover, inclusive TFP was calculated by using the super-efficiency SBM model and the Malmquist index, taking capital

Table 1
Evaluation index system of high-quality economic development.

Primary indexes	Secondary indexes	Index interpretation	Attributes
Industrial structure	Industrial structure rationalization	A modified Thiel index	–
	Advanced industrial structure	The ratio of the added value of the tertiary industry to the secondary industry	+
	Proportion of producer services	The proportion of producer services in urban employment	+
Inclusive TFP	Inclusive TFP index	Measured by the DEA Malmquist productivity index method	+
Technology innovation	Patent license	Number of patents granted per 10,000 people	+
Ecological environment	Industrial wastewater discharge	Industrial wastewater discharge per capita	–
	Industrial sulfur dioxide emissions	Industrial sulfur dioxide emissions per capita	–
	Industrial smoke (powder) dust emissions	Industrial smoke (powder) dust emissions per capita	–
	PM2.5	Annual average PM2.5 concentration	–
Residents' living standards	GDP per capita	GDP/permanent urban population	+
	Education spending	Expenditures on education per capita	+
	Number of hospital beds	Number of hospital beds per capita	+

and labor as input factors, the GDP as the expected output, and the urban-rural income gap as the unexpected output.

Finally, the entropy method was applied to measure high-quality urban economic development. The advantage of this method is that the entropy value is used to determine the index weights, which can help overcome the problem of randomness of subjective assignment and solve the issue of overlapping information among the multiple index variables.

3.1.2. Core independent variable: the digital economy

This study used the establishment of big data comprehensive pilot zones to measure the digital economy. In this case, the pilot cities take on a value of 1, or 0 for the non-pilot cities. In addition, the year when a national big data comprehensive pilot zone is established and the subsequent years take on a value of 1, or 0 before policy implementation (Li et al., 2022a, 2022b, 2022c, 2022d).

The list of big data comprehensive pilot zones was obtained from the official website of the MIIT.¹ A total of 67 cities were used as the treatment group, while the remaining 216 cities served as the control group. Although all of the big data comprehensive pilot zones were approved in 2016, Guizhou Province started its construction in September 2015. Thus, to improve the accuracy of policy identification, the policy implementation date was set to 2015 for Guizhou Province and to 2016 for the other cities in this study.

3.1.3. Control variables

To accurately assess the impact of the digital economy on high-quality urban economic development, this study followed existing literature (Ma et al., 2022) and selected the following control variables.

- (1) The level of economic development (*pgdp*): Expressed in terms of the regional GDP per capita. High GDP per capita means that the city has better resource endowment conditions, while the increase in the quantity of economic growth is the basis for quality improvement (Awan and Azam, 2022).
- (2) Population size (*poe*): Measured by the number of permanent residents in the city. According to related literature (Bai and Lei, 2020; He and Mao, 2016), China's economic growth has been sustained over the past four decades, due to the transformation of the demographic dividend into productivity from its reforms and opening-up.
- (3) Foreign direct investment (*fdi*): Expressed in terms of the ratio of the amount of real foreign direct investment to the GDP. Foreign direct investment optimizes the resource allocation efficiency of host countries by bridging the capital gap, promoting employment, enhancing local human capital, introducing technology, and generating technology spillovers to promote its economic growth (Chang and Li, 2019).
- (4) The level of financial development (*finance*): Expressed as the ratio of the deposits and loan balances of financial institutions to the GDP at the end of the year. Many studies have shown that financial development can reduce information asymmetry and contract defects to reduce financing constraints. It can also reduce the external financing costs of enterprises and improve the efficiency of capital formation, thus having a positive impact on TFP and ultimately, on economic growth (Hunjra et al., 2022).
- (5) Industrial structure upgrading (*ish*): Expressed as the share of the added value of the tertiary industry in the GDP. The development experience of advanced industrialized countries shows that the transformation and upgrading of industrial structure is critical for ensuring that the economy continues to move to a higher level (Guo and Liu, 2022).

¹ For more information, please see: https://www.miit.gov.cn/ztzl/lszt/tddsjcyfz/sdsf/art/2020/art_59cc06f2e0604858a60ab35c6b0319de.html.

The descriptive statistics for the main variables are presented in Table 2.

The present study also created a trend chart of the high-quality economic development levels of the treatment and control groups (Li et al., 2022a, 2022b, 2022c, 2022d). The trend of high-quality economic development is presented in Fig. 2. As shown in this figure, since the policy implementation, the treatment group's growth rate of high-quality economic development was significantly higher than that of the control group. Furthermore, the gap between them gradually widened, providing additional evidence that the policy implementation promoted high-quality urban economic development. However, since the trend chart based on the mean value was also affected by time trends and other related factors, the impact of the digital economy has not been fully confirmed. Hence, we employed an econometric model to analyze the relationship between the digital economy and high-quality urban economic development with greater depth and accuracy.

3.2. Model settings

The DID method can efficiently identify the causal effect of the external policy shocks by comparing the net effect between the treatment and control groups. Thus, we applied the DID method to examine the impact of the digital economy on high-quality economic development.² The DID estimation specification is expressed as follows (Beck et al., 2010):

$$hqdi_t = \beta_0 + \beta_1 did_{it} + \beta_c X_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (1)$$

$$\text{where } did_{it} = group_i \times time_t \quad (2)$$

where $hqdi_t$ expresses high-quality economic development for city i in year t ; $group_i$ represents city dummies (with a value of 1 if city i is affected by the policy, or 0 otherwise); $time_t$ is a time dummy variable that takes on a value of 1 for the year when the national big data comprehensive pilot zones were established and for the subsequent years, or 0 otherwise; X_{it} represents other control variables; γ_t represents the year-fixed effect; μ_i represents the city-fixed effect; and ε_{it} is a random error term. At the same time, the robust standard errors were clustered at the city level during estimation. To a certain extent, the model effectively controlled for the differences and time trends between the treatment and control groups.

Table 2
Descriptive statistics for the variables.

Variables	Observations	Mean	Standard deviation	Minimum	Maximum
<i>hqdi</i>	4245	0.079	0.050	0.021	0.541
<i>did</i>	4245	0.064	0.245	0	1
<i>lnpgdp</i>	4245	10.35	0.760	4.595	13.06
<i>poe</i>	4245	0.044	0.031	0.002	0.342
<i>fdi</i>	4245	0.021	0.046	0.001	1.371
<i>lnfinance</i>	4245	0.727	0.664	−8.424	10.27
<i>ish</i>	4245	0.422	0.118	0.004	0.853

² The stable unit treatment value assumption (SUTVA) is one of the assumptions that must be satisfied when using the DID model. The implication is that the policy intervention only affects the treatment group and does not interact with the control group, or that there are no spillover effects from such intervention. However, we did not have a way to directly test this assumption and could only counter prove it based on the policy context. Considering that this study examined policy implementation, and China is a centralized country, a province must obtain approval from the central government if it wants to implement a certain policy. Thus, it can be assumed that this policy will only have an impact on the treatment group.

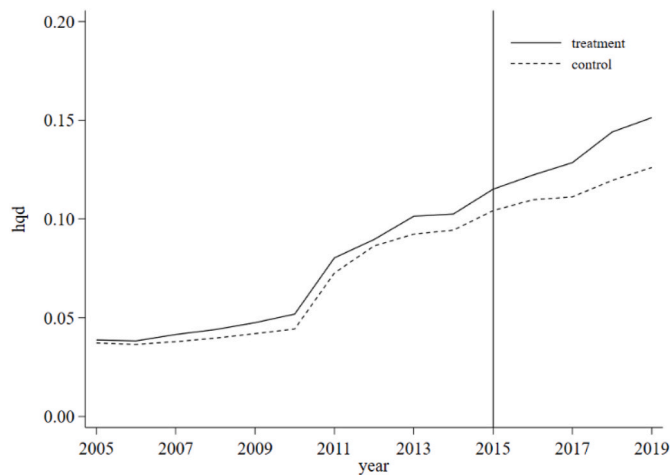


Fig. 2. The trend of high-quality economic development.

4. Results and discussion

4.1. Parallel trend test

This study applied the DID model to identify the causal effects of the big data comprehensive pilot zones on high-quality urban economic development. In this regard, we compared the changes over time in a group unaffected by the policy intervention to the changes in a group affected by such intervention (Roth, 2022). Meanwhile, the most crucial premise of using the DID model was to satisfy the parallel trend hypothesis. Before establishing the big data comprehensive pilot zones, the high-quality urban economic development levels of the control groups showed the same change trend. To confirm this, the big data comprehensive pilot zones' influence lags and leads were tested, the results of which are presented in Fig. 3.

Fig. 3 clearly shows that the coefficients of the policy variables were insignificant before the establishment of the big data comprehensive pilot zones. This indicates that there is no significant difference in the level of high-quality economic development between the treatment and control groups before policy implementation. In addition, the estimated coefficients were significantly positive in the first year after policy implementation, and became more prominent as the years progressed. This suggests that the establishment of the big data comprehensive pilot zones makes a long-term contribution to high-quality urban economic development, with the influence increasing over time. Therefore, the parallel trend hypothesis is verified.

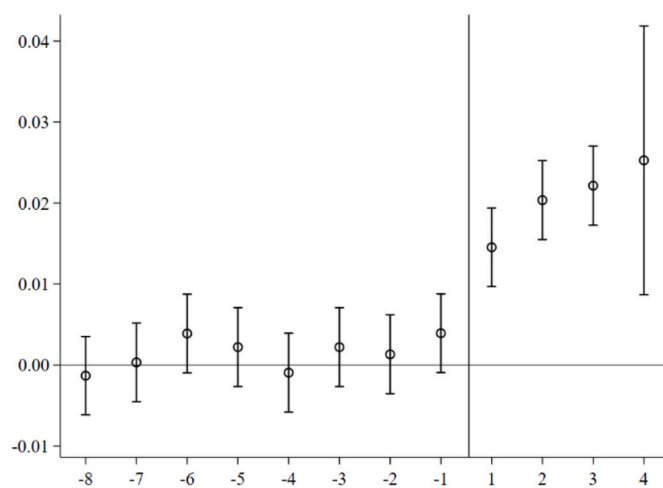


Fig. 3. A common trend test.

4.2. Main results

Table 3 presents the empirical results of evaluating the net effect of the big data comprehensive pilot zones on high-quality urban economic development. In this case, the average effect is captured by the estimated coefficient of the policy dummy variable. This variable's coefficient is also positive and statistically significant at the 1% or 5% critical level in each regression.

The first two columns of Table 3 include the benchmark regression results of the DID model. The results in Column (1) are based on controlling the city-fixed effects and year-fixed effects. The coefficient is significantly positive at the 1% level when only including the policy dummy variable. However, after adding the control variables, the core independent variable in Column (2) is still significantly positive at the 1% level. This preliminarily confirms that the development of the digital economy is conducive to promoting the quality of economic development in Chinese cities. Hence, the government should continue to construct big data comprehensive pilot zones and fully exploit the growth quality effect of the digital economy.

The results of the control variables are as follows. First, there is a significant positive correlation between the level of economic development (*pgdp*) of each city and high-quality economic development, indicating that an increase in the quantity of economic growth is a prerequisite for qualitative improvement. Second, the coefficient of population size (*poe*) is significantly positive, indicating that China's demographic dividend still exists and is providing important support for sustainable economic development. Third, the coefficient of foreign direct investment (*fdi*) is negative, but insignificant. This shows that foreign investment does not improve high-quality urban economic development. The main reason may be that the quality of foreign investment in China is not high, since it is dominated by industries with high pollution and high energy consumption. At the same time, it is relatively easy to form technology dependence in attracting foreign investment, which is not conducive to improving China's innovation level. Finally, the positive coefficients of the level of financial development (*finance*) and the upgrade of industrial structure (*ish*) show that developing a high-level capital market and promoting the balanced development of industrial structure are beneficial for increasing the quality of urban economic growth.

Moreover, to overcome the possible systematic differences in the high-quality economic development levels between the treatment and

Table 3

Effects of big data comprehensive pilot zones on high-quality urban economic development.

	DID		PSM-DID	
	(1)	(2)	(3)	(4)
<i>did</i>	0.0141*** (0.0054)	0.0157*** (0.0053)	0.0144** (0.0056)	0.0145*** (0.0054)
<i>lnpgdp</i>		0.0143*** (0.0053)		0.0180*** (0.0063)
<i>poe</i>		0.0184*** (0.0038)		0.0136*** (0.0001)
<i>fdi</i>		-0.0163 (0.0297)		-0.0208 (0.0240)
<i>lnfinance</i>		0.0046* (0.0024)		0.0073** (0.0036)
<i>ish</i>		0.0521*** (0.0120)		0.0661*** (0.0141)
Constant	0.0783*** (0.0003)	-0.0972* (0.0573)	0.0782*** (0.0003)	-0.1360** (0.0679)
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes
Observations	4245	4245	4228	4228
R-squared	0.842	0.861	0.842	0.856

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

control groups (which may lead to biased estimation results), this study used the PSM-DID method to alleviate possible selectivity bias and avoid the endogenous problem (Fan and Zhang, 2021). Specifically, we used high-quality urban economic development as the outcome variable, applied the control variables in the benchmark model as covariates, and performed the corresponding matching according to the one-to-one neighbor matching method with put-back. Fig. 4 presents the distribution of the propensity scores before and after matching. Meanwhile, according to the PSM method principles, a common support hypothesis test was conducted, the results of which are shown in Table 4. The findings indicate that the matching result of PSM is reasonable. Based on Columns (3) and (4) in Table 3, which show the regression results for the PSM-DID method, the parameter estimations are significantly positive.

4.3. Instrumental variable estimation

The main findings prove that the digital economy can promote high-quality urban economic development. However, there may be some endogenous problems due to reverse causality and omitted variables. Specifically, the selection of the big data comprehensive pilot zones may not be entirely random. Meanwhile, some control variables that are difficult to observe, but have a significant impact on high-quality economic development, may be omitted in the model's setting. Thus, this study adopts the instrumental variable (IV) method to control for possible endogeneity issues and identify the net effect.

By referring to previous literature (Zhao et al., 2020), the historical data of posts and telecommunications in 1984 was selected as the instrumental variable of the digital economy to re-estimate the model. At the same time, since the historical data is cross-sectional, it cannot be directly applied to the regression model. Hence, drawing on existing literature (Nunn and Qian, 2014), the number of international internet users in the previous year and the number of telephones per 10,000 people in the city in 1984 were multiplied to construct an interaction term and use it as an instrumental variable for the digital economy.

Table 5 presents the estimation results. Column (1) includes the regression results of the first stage of the two-stage least squares (2SLS) method, and shows that the findings pass the instrumental variable under-identification and weak instrumental variable tests. According to Column (2), which presents the results of the second-stage regression, the digital economy promotes high-quality urban economic development. Additionally, its estimated coefficient is larger than the baseline regression, indicating that the impact of the digital economy is stronger after the endogeneity is mitigated.

4.4. Robustness checks

4.4.1. Placebo test

This study randomly selected 67 cities as the treatment group and a year as the policy implementation time for counterfactual testing (Li et al., 2016). Our study repeated 1000 estimates based on the benchmark regression results in Column (2) of Table 3. The results of the kernel density distribution of the placebo test are shown in Fig. 5. As shown in this figure, the estimated coefficients center around 0, while the benchmark regression result of 0.0157 is outside the distribution. This indicates that the randomly established big data comprehensive pilot zones have no policy implications, and demonstrates that the benchmark regression results are unaffected by other no-observation factors.

4.4.2. Excluding the impact of other policies

In the process of estimating the impact of the digital economy on high-quality economic development, other related policies will inevitably lead to an overestimation of the effect of policy implementation. To solve this problem, we added other relevant policy variables to the benchmark regression model by referring to previous literature. First, Li et al. (2020) confirmed that high-speed rail can improve the quality of

urban economic growth, and it has a positive impact on high-quality urban economic development, primarily through labor mobility. Second, the Broadband China policy has a significant effect on improving urban TFP (Ren et al., 2022). Based on this, we believe that the policy will also have an impact on high-quality urban economic development. Third, four components of Innovative City Construction can increase the quality of urban economic growth: fiscal expenditure bias, structural endowment, human capital, and market demand (Du and Li, 2022). Consequently, it is more appropriate to include high-speed rail, Broadband China, and Innovative City Construction in the benchmark regression model to investigate the net effect of the digital economy.

According to the results shown in Table 6, high-speed rail, Broadband China, and Innovative City Construction have a significant positive impact on high-quality urban economic development, among which Innovative City Construction has the most significant impact. Meanwhile, although the coefficient of the digital economy remains significantly positive after the inclusion of three policy variables, the coefficient value becomes smaller. This indicates that the digital economy's impact on high-quality urban economic development may be overestimated. However, its promotion effect is still significant.

4.4.3. Other robustness checks

The following robustness checks were carried out in our study, including.

- (1) To better control the interference of policy factors and other random factors over time in each province, this study controlled for the joint fixed effects of the province year and re-estimated them.
- (2) Due to the possibility of outliers in the sample, all continuous-type variables in this study were shortened by 1% and re-estimated.
- (3) This study used the TFP index to measure high-quality urban economic development (Pan et al., 2022) and re-estimated it.
- (4) Since municipalities directly under the central government, provincial capitals, and sub-provincial cities significantly differ from ordinary prefecture-level cities, it can lead to biased estimation results. Thus, we deleted the municipalities directly under the central government, provincial capitals, and sub-provincial cities from the sample data, and only measured the sample of ordinary prefecture-level cities (Li et al., 2022a, 2022b, 2022c, 2022d) and re-estimated it.
- (5) This study further used a counterfactual method to conduct a placebo test. After artificially setting a policy implementation node and testing its impact effect, the insignificant coefficient indicates that the digital economy drives high-quality urban economic development. Therefore, we selected 2013 and 2014 as the time points for establishing the big data comprehensive pilot zones and then re-estimated them. All of the results are shown in Table 7.

5. Further analysis

5.1. Channel analysis

Based on the previous theoretical analysis, this section empirically tests the influence mechanism between the digital economy and high-quality urban economic development. By referring to related literature (Nemlioglu and Mallick, 2020), we established the following model to explore the transmission mechanism of the digital economy affecting high-quality urban economic development:

$$hqd_{it} = \theta_0 + \theta_1 did_{it} + \theta_2 mech_{it} + \theta_3 did_{it} \times mech_{it} + \theta_c X_{it} + \gamma_i + \mu_t + \varepsilon_{it} \quad (3)$$

where $mech_{it}$ represents the mechanism variables, including human

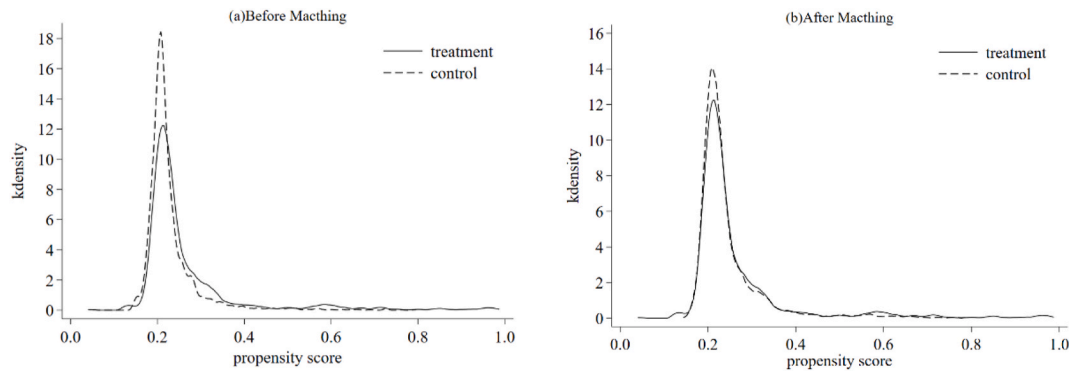


Fig. 4. Results of the kernel density distribution of the propensity scores before and after matching.

Table 4

Results of the common support hypothesis test.

		Mean (Treated)	Mean (Control)	Bias (%)	t- value	p- value
<i>lnpgdp</i>	Unmatched	10.46	10.31	19.3	5.28	0.00
	Matched	10.45	10.43	1.2	0.24	0.81
<i>poe</i>	Unmatched	0.50	0.47	5.8	1.66	0.09
	Matched	0.50	0.50	0.1	0.02	0.98
<i>fdi</i>	Unmatched	0.02	0.02	4.8	1.13	0.26
	Matched	0.02	0.04	-3.1	-0.57	0.57
<i>lnfinance</i>	Unmatched	0.72	0.73	-1.1	-0.31	0.76
	Matched	0.70	0.73	-4.1	-0.95	0.34
<i>ish</i>	Unmatched	0.43	0.42	13.1	3.67	0.00
	Matched	0.43	0.44	-6.3	-1.42	0.16

Table 5

Instrumental variable regression results.

	First Stage (1)	Second Stage (2)
<i>iv</i>	0.0083*** (0.0016)	
<i>did</i>		0.0571*** (0.0147)
Control variables	Yes	Yes
City F.E.	Yes	Yes
Year F.E.	Yes	Yes
Kleibergen-Paap rk LM Statistics		7.426***
Kleibergen-Paap rk Wald F Statistic		18.136
Observations	3345	3345
R-squared	0.836	0.761

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

capital and green technology innovation. Additionally, human capital (*human*) is represented by the ratio of the number of students in ordinary colleges and universities to the total population at the end of the year, while green technology innovation (*gtp*) is represented by the number of green patent authorizations per 10,000 people. The definitions of the other variables are the same as those in Eq. (1). The regression results are shown in Table 8.

Columns (1) and (2) in Table 8 show that the coefficient of $did \times human$ is significantly positive, regardless of whether control variables are added. This indicates that human capital is a key resource for promoting high-quality development. Meanwhile, by adding the interaction term between the digital economy (*did*) and green technology innovation (*gtp*) to the baseline regression model, the results show that its coefficient is also significantly positive. This suggests that the digital economy promotes a level of green innovation from both macro and micro perspectives, thus providing a driving force for high-quality urban

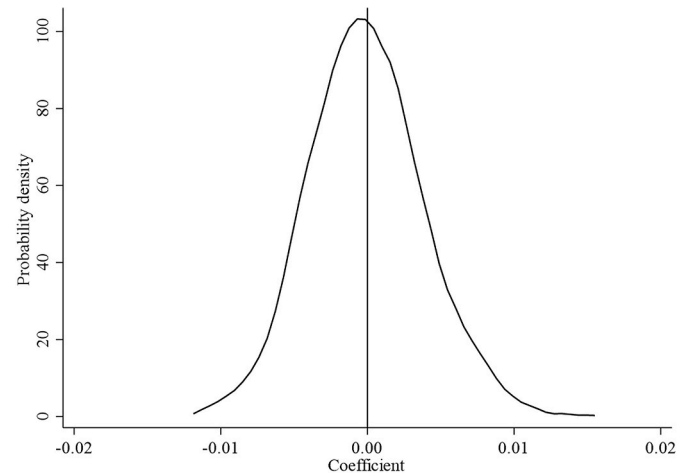


Fig. 5. Results of the kernel density distribution of the placebo test.

Table 6

Results of excluding other policies.

	(1)	(2)	(3)	(4)
<i>did</i>	0.0147*** (0.0053)	0.0149*** (0.0054)	0.0137*** (0.0053)	0.0128*** (0.0015)
High-speed rail	0.0038* (0.0023)			0.0023** (0.0011)
Broadband China		0.0060* (0.0033)		0.0039*** (0.0013)
Innovative City			0.0130*** (0.0037)	0.0117*** (0.0014)
Construction				
Control variables	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes
Observations	4245	4245	4245	4245
R-squared	0.861	0.862	0.864	0.894

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

economic development. In sum, the digital economy drives high-quality urban economic development by promoting human capital and improving green technology innovation.

5.2. Heterogeneous effects

5.2.1. Heterogeneity of city location and city size

According to the city location and size, the study sample was divided into eastern, central, and western cities, as well as small and large cities (Wu et al., 2022). Specifically, the division of city locations was mainly

Table 7
Results of other robustness checks.

	Joint fixed effects	Eliminate outliers	Replace the explained variable	Delete center city	Counterfactual test
	(1)	(2)	(3)	(4)	(5)
<i>did</i>	0.0157*** (0.0054)	0.0105*** (0.0037)	0.0082* (0.0043)	0.0133** (0.0052)	0.0123 (0.0092)
Control variables	Yes	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes	Yes
Observations	4245	4245	4245	3720	4245
R-squared	0.861	0.886	0.852	0.867	0.859

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 8
Results of the channel analysis.

	(1)	(2)	(3)	(4)
<i>did</i>	0.0054** (0.0024)	0.0046** (0.0019)	0.0044*** (0.0016)	0.0036* (0.0019)
<i>human</i>	0.2021* (0.1148)	0.1303* (0.0704)		
<i>did</i> × <i>human</i>	0.4071** (0.1832)	0.5150*** (0.1851)		
<i>gap</i>			0.1010*** (0.0075)	0.0959*** (0.0069)
<i>did</i> × <i>gtp</i>			0.0861** (0.0340)	0.0907** (0.0382)
Control variables	NO	Yes	NO	Yes
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes
Observations	4245	4245	4245	4245
R-squared	0.844	0.865	0.886	0.902

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

based on the province to which the city belonged.³ Meanwhile, the classification of city size was mainly based on the “Notice on Adjusting the Criteria for Urban Size Division” issued by the State Council in 2014. In our study, cities with a permanent population of more than three million were regarded as large cities, while those with less than three million were considered as small cities.

Table 9
Estimation results of city location and city size.

	City location		City size	
	Eastern	Central and western	Large	Small
	(1)	(2)	(3)	(4)
<i>did</i>	0.0203** (0.0092)	0.0048*** (0.0017)	0.0290* (0.0161)	0.0074* (0.0039)
Control variables	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes
Observations	1500	2745	600	3645
R-squared	0.852	0.888	0.852	0.882

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

³ The eastern region includes: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central and western regions include: Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

As shown in Table 9, compared with the cities in the central and western regions as well as small cities, the estimated coefficient of the cities in the eastern region and large cities is greater, i.e., the digital economy has a more substantial effect on high-quality economic development in the eastern region and large cities. From the perspective of city size, previous research has shown that city size significantly impacts high-quality economic development. On the one hand, large cities have the advantages of the economic agglomeration effect and talent concentration, which can promote the quality of economic growth by optimizing resource allocation and promoting industrial structure upgrading (Frick and Rodriguez-Pose, 2018). On the other hand, the expansion of city size is accompanied by the crowding effect. Some issues, including resource overuse, rising pollution, and urban congestion, significantly impede the achievement of high-quality economic development (Mohajeri et al., 2015). However, the digital economy can alleviate the congestion effect faced by large cities in economic development, further exploit their resource allocation advantages, and lay a good foundation for high-quality urban economic development. From the perspective of city location, the eastern region has a better economic foundation and resource endowment, a richer talent pool, and more financial expenditures. Thus, the digital economy in these cities can more significantly and efficiently promote high-quality economic development.

5.2.2. Heterogeneity of the city characteristics

The role of the digital economy in promoting high-quality economic development can vary, depending on city characteristics. To analyze the heterogeneity of city characteristics, it is necessary to select the specific characteristics of cities that promote the development of the digital economy or impact high-quality economic development (Liu et al., 2022a, 2022b). Thus, we examined the impact of the digital economy on high-quality economic development in terms of innovation capacity and internet development, respectively. In our study, innovation capacity was expressed in terms of the number of patents granted per 10,000 people in a city, while internet development was considered in terms of the number of international internet users.

According to the regression results in Table 10, the digital economy has a more significant estimation coefficient in cities with high innovation capability and internet development. Therefore, technology innovation and the internet are critical elements for the digital economy to promote high-quality economic development. In this regard, to avoid blindly copying the development concepts of other regions, local governments should target their planning and development based on local resource endowments and improve the inclusiveness and flexibility of the implementation the big data comprehensive pilot zone strategy, so that the digital economy can fully impact the quality of economic growth.

Table 10

Regression results for cities with different innovation capacity and Internet development.

	Innovation capacity		Internet development	
	Low	High	Low	High
	(1)	(2)	(3)	(4)
<i>did</i>	0.0044* (0.0026)	0.0195*** (0.0061)	0.0056 (0.0040)	0.0141** (0.0059)
Control variables	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes
Observations	2118	2127	2120	2112
R-squared	0.861	0.905	0.902	0.887

Note: (1) The values in parentheses are robust standard errors clustered at the city level; (2) ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

6. Conclusions and policy implications

6.1. Conclusions

In this new era of big data, it is a driving force that plays a key role in improving the quality of urban economic growth. Meanwhile, the establishment of big data comprehensive pilot zones provides a background for examining the impact of the digital economy. Hence, this study adopted the DID and PSM-DID models to assess how the digital economy affects high-quality urban economic development.

The findings are as follows. First, the digital economy can significantly improve high-quality urban economic development. Second, the results were confirmed to be robust and reliable through a series of robustness tests. Third, the channel analysis showed that the digital economy can improve human capital and promote green technology innovation. Fourth, the digital economy had a more substantial impact in the eastern region and large cities. Finally, cities with high innovation capability and high internet development can significantly enhance the driving effect of the digital economy on high-quality development.

To the best of our knowledge, this study is the first to determine whether the digital economy, due to the establishment of big data comprehensive pilot zones, can promote high-quality urban economic development. The following are some notable contributions. First,

unlike previous literature that only examined the impact of the digital economy in different geographical locations (Ding et al., 2022; Sun et al., 2022), we analyzed it in terms of city location, size, and characteristics. Second, we further extend the research on the drivers of high-quality urban economic development by including the dual effects of human capital and green technology innovation, introducing a new avenue for enhancing economic development (Liu et al., 2022a, 2022b; Yu and Zhou, 2021; Zhao et al., 2020).

6.2. Policy implications

Based on the findings, this study proposes the following policy recommendations. First, the Chinese government should comprehensively promote the development of the digital economy and make it a sustainable driving force for high-quality economic development. This can accelerate the evolution of digital industrialization and industrial digitization, further promoting the depth and breadth of the integration of the digital economy and the real economy. Meanwhile, it is necessary to improve the effects of the digital economy on high-quality urban economic development in the central and western regions of China. Second, it is important to explore the multidimensional path of the digital economy to promote the high-quality development of the urban economy, make full use of the convenience of big data, break down barriers, and promote the efficient flow of resource elements. Third, the Chinese government should promote the construction of information infrastructure, accelerate the popularization of the internet, and lay the foundation for the role of big data. Besides, the development of big data-related industries is inseparable from improving information infrastructure. Therefore, it is necessary to further enhance the speed and efficiency of information transmission and create favorable conditions for the digital economy to drive high-quality economic development.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Appendix A. The specific steps of the entropy method

① Present the non-dimensional treatment of indicators:

$$\text{Positive indicators : } D_{ij} = \frac{X_{ij} - \min\{X_{1j}, \dots, X_{nj}\}}{\max\{X_{1j}, \dots, X_{nj}\} - \min\{X_{1j}, \dots, X_{nj}\}} \quad (\text{A1})$$

$$\text{Negative indicators : } D_{ij} = \frac{\max\{X_{1j}, \dots, X_{nj}\} - X_{ij}}{\max\{X_{1j}, \dots, X_{nj}\} - \min\{X_{1j}, \dots, X_{nj}\}} \quad (\text{A2})$$

where X_{ij} is the j index of the city I , $i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$.

② Construct the normalized matrix:

$$Q_{ij} = D_{ij} / \sum_{i=1}^n D_{ij} \quad (\text{A3})$$

③ Calculate the entropy value of the j index:

$$M_i = -k \sum_{i=1}^n Q_{ij} \ln Q_{ij} \quad (\text{A4})$$

where $k = \frac{1}{\ln n} > 0$.

④ Calculate the redundancy of information entropy:

$$S_j = 1 - M_j \quad (\text{A5})$$

⑤ Calculate the index weight:

$$W_j = S_j / \sum_{j=1}^m S_j \quad (\text{A6})$$

⑥ Calculate the development level of the digital economy:

$$E_i = \sum_{j=1}^m W_j Q_{ij} \quad (\text{A7})$$

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