Heliyon 10 (2024) e39583

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

The impact of digital policies on urban economic resilience under the low-carbon background: A deep identification based on environmental regulation and industrial digital transformation

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A R T I C L E I N F O

Keywords:
Digital policy
Economic resilience
Environmental regulation
Digital transformation
Nonlinear effects

A B S T R A C T

With over exploitation and increasingly severe environmental pollution, traditional economic growth models are no longer able to promote high-quality regional economic development. Especially in recent years, the limitations of resources and environment, global geopolitical conflicts, and other factors have brought enormous uncertainty to the economic development of each country. To cope with the uncertainty of economic development, it is necessary to use the digital economy formed by the new generation of information technology to strengthen the economic resilience of various regions. This study collected panel data from 30 provinces and cities in China from 2013 to 2022, using the PSM-DID model to examine the subtle relationship between the formulation of digital policies in different cities and their economic resilience. Specifically, environmental regulations and industrial digital transformation play an important role in the process of urban digital policies affecting economic resilience. The research findings of this article emphasize the crucial role of digital policies in addressing the current challenges of economic uncertainty. Through empirical research, the results show that the strategic implementation of digital policies can not only effectively promote the digital transformation of traditional industries, but also strengthen the role of environmental regulations in promoting sustainable development of industries. The digital transformation of industries and sustainable development will significantly enhance regional innovation capabilities and ultimately strengthen regional economic resilience.

1. Introduction

In recent years, the world is experiencing unprecedented changes, with factors such as geopolitics, protectionism, unilateralism and climate change influencing both developing and developed countries. Within this intricate web of internal and external factors, urban development stands vulnerable to natural and societal fluctuations. China's "14th Five-Year Plan" unveiled in2021,[1] advocates for embracing novel trends in urban development. It calls for pilot demonstrations of urban modernization, aiming to construct resilient cities that are not only livable, innovative, and smart but also environmentally conscious and people oriented. Currently, if cities want to achieve sustainable and high-quality development, the uncertainty factors of these developments must be highly considered. Urban

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[1] content from website: https://en.ndrc.gov.cn/policies/202203//P020220315511326748336.pdf.

https://doi.org/10.1016/j.heliyon.2024.e39583
Received 9 April 2024; Received in revised form 17 October 2024; Accepted 17 October 2024
Available online 18 October 2024
2405-8440/

economic resilience becomes paramount—an urban area's ability to swiftly adapt, recover, and uphold its developmental features in the face of unforeseen environmental shifts along its growth trajectory. Therefore, analyzing how urban development can cope with the impact of the uncertain development environment from a resilience perspective is a crucial topic for achieving high-quality development for cities in the future, given today's increasingly complex socio-economic development situation.

The digital economy, which has made significant progress in the past few years (Fig. 1),[2]is an emerging form of economy that relies on emerging information technologies such as artificial intelligence and big data. It can integrate digital technology with physical industries, foster industrial innovation and development, and enhance its capacity to cope with external environmental uncertainties. The development of the digital economy is inherently linked to the guidance provided by digital policies. Through the resonance effect of digital policies and other factors, it can provide a good public service mechanism and social business environment, promote enterprises to actively carry out digital transformation, make full use of digital technologies and resources, optimize enterprise operation and management and product services [1], and continuously improve the quality and efficiency of enterprise development, thereby enhancing the level of regional economic development and further improving the city's ability to withstand external shocks. Meanwhile, the direction of today's technological revolution and industrial transformation is green and low-carbon development, which is essential for high-quality development [2]. According to Gu(2023), industrial development has been strengthened by the digital transformation in policy formulation and regulation from the perspective of green and sustainable development, thus putting forward new transformation requirements for various traditional production factors [3]. This reverse force mechanism of factor upgrading indirectly strengthens connotative development and helps to enhance regional economic resilience. In addition, Li(2024) suggested that digital transformation can optimize the corporate governance structure, reduce agency costs, attract more external scrutiny, motivate management to focus on long-term goals, and stimulate the willingness for green innovation [4]. Therefore, sorting out the relationship between digital policy, environmental regulation, industrial digital transformation and economic resilience is of great significance in guiding the enhancement of economic resilience in China's cities.

2. Literature review

The existing research on economic resilience can be divided into three aspects: first, the connotation of economic resilience. According to Boschma(2017), economic resilience is the capacity of an economy to cope with economic shocks by changing and rearranging its structure to follow existing or new growth trajectories [5]. Walker et al. (2004) consider economic resilience to be the ongoing evolution of the economic system, which develops and innovates under the impact of shocks and various factors [6]. Although both views are reasonable, the former emphasizes the adaptability of economic resilience in the face of shocks, while the latter emphasizes economic resilience's transformative abilities. However, there is clearly a strong correlation between adaptability and transformation ability, so economic resilience should include both adaptability and transformation ability. According to existing research, Martin and Sunley (2015) propose a more comprehensive definition of economic resilience, which consists of four dimensions: resistance, recovery, adjustment, and innovation transformation [7]. This definition has gained wide acceptance among scholars [8,9]. Secondly, economic resilience measurement and evaluation. There are mainly two ways to measure: multidimensional indicators and single dimensional indicators. The multidimensional indicator measurement method is to measure economic resilience through the construction of an indicator system. Wang et al. (2022) measures economic resilience through a composite of five subsystems: the economic performance subsystem, the public opinion subsystem, the public health subsystem, the policy support subsystem, and the pandemic shock subsystem [10]. While Xie et al. (2018) assessed economic resilience based on both the recovery capacity and the recovery speed [11]. In comparison, unidimensional metrics measurement only uses one factor to capture a feature or a dimension of the analyzed object. Shang (2024) uses the difference between the real growth rate of the regional economy and the real growth rate of the national economy as a whole to measure economic resilience [12]; He (2024) used the Regional Sensitivity Index to measure the economic resilience (based on GDP) [13]. Thirdly, research on the influencing factors of economic resilience. Previous research has identified that economic output, employment, green finance, trade openness and economic specialization exert all have significant impacts on economic resilience [14–18]. However, it is noteworthy that the existing research on economic resilience has relatively limited discussion on the potential effects of digital policies.

In fact, the implementation of digital policies can effectively promote digital technology transformation in multiple dimensions such as macro planning, industry guidance, and micro incentives, especially in promoting the deep integration of digital technology and the real economy. This "digital industry" integration helps to further expand the construction of the digital application ecosystem, thereby enhancing the regional economy's ability to resist external economic uncertainty. Gruber (2019) believes that digital industrial policy can stimulate the creation and adoption of productivity-enhancing digital services and promote the development and prosperity of the European economy by accelerating the construction of ultra-high-speed broadband networks and adoption of productivity enhancing digital services [19]. In addition, in the context of high-quality development, green and sustainable development has become the key to the development of new economic forms, in which environmental regulation undoubtedly plays an important role. Lăzăroiu et al.(2020) argues that social and environmental constraints may be decisive for organizational sustainability performance [20]. Acemoglu et al. (2012)suggests that environmental regulation can stimulate innovation in the clean sector, that is, when inputs are sufficiently substitutable, innovation can be shifted to cleaner inputs through temporary taxes/subsidies, leading to sustainable growth [21]. Krysiak (2011) point out that effective environmental regulation environmental regulation can enhance the

[2] Due to limitations in data acquisition, this article only presents the scale of the digital economy in several countries. The data cited is from the China Academy of Information and Communications Technology.

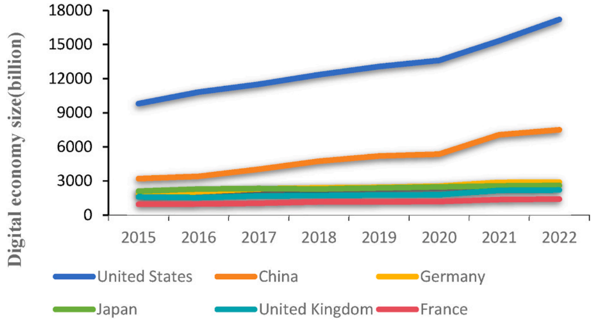

Fig. 1. The scale of digital economy in major countries.

internal motivation for business change, encourage firms to use greener technologies, and foster the innovation capacity of firms in an eco-friendly manner [22]. Additionally, environmental regulations are also spatial in nature. Wu et al.(2022) notes that environmental regulation have a significant effect on the total factor productivity of the pharmaceutical manufacturing industry in the local and neighboring regions [23]. The improvement of enterprise innovation ability can further amplify the positive effect of digital policy on industrial development, which will greatly boost the regional economic resilience.

To sum up, the development level of digital industrialization and appropriate environmental regulations will have a certain impact on the governance effect of digital policies on the elastic development of regional economies. Research on the impact mechanism of incorporating environmental regulations and industrial digital transformation into digital policy implementation on improving urban economic resilience has certain theoretical and practical significance.

3. Theoretical analysis and research hypotheses

3.1. The impact of digital policies on urban economic resilience

Digital technology is more and more responsive to the individual preferences of consumers, connecting the physical and digital realms more closely [24]. It also boosts high-quality socio-economic development and speeds up the digital change of industries with its advantages. The digital economy, as an economic development model centered on digital technology, has been widely used around the world.

Digital policy, as a precursor measure of the government's economic governance, can effectively guide the pooling of digital resources, promote the construction of digital ecological pluralism, effectively enhance the efficiency of industrial transformation and upgrading, and then promote the sustained and high-quality development of the economy and society.

By formulating and implementing digital policies, cities have the potential to effectively facilitate the seamless integration of information technology and physical industries. This can result in the enhancement of the technology spillover effect within industrial development, thereby promoting the optimization and upgrading of urban industrial structure. As a result, cities can achieve high-quality development in industrial innovation. Additionally, the application of digital technology can substantially enhance the government's urban management and service capabilities, allowing for a more rapid and flexible response to various internal and external economic uncertainties and impacts and the government is able to collect, validate and update regional transaction information in real time, which improves the security and validity of the transactions, and which provides a certain level of security for the city [25]; Furthermore, the digital policy is in place to ensure the stability of enterprise data resources at the source [26], digital technologies can be used to efficiently detect and manage urban resources, clarify the allocation of various industries and innovative resources, and effectively exploit the inherent economic potential of urban areas. Propose research hypotheses:

H1. The implementation of digital policies can have a significant impact on improving the economic resilience of urban areas.

3.2. The role of industrial digital transformation

The impact of digital policies on economic resilience is reflected in its adjustment of industrial structure, optimization of resource allocation, and improvement of service capabilities. Industrial digital transformation is an important way to combine information technology with real industries, and is an important link in the optimization of regional industrial structure [27]. By formulating and implementing digital policies, industrial digital ecology can be constructed, traditional industries can be transformed and upgraded, and urban economies can be made more resilient. On the one hand, under the role of digital policy, governments at all levels have increased the construction of digital infrastructure and integrated various infrastructure resources, thus reducing the application cost of digital technology [28]. Meanwhile, a favorable legal environment and a supportive political environment reduce the costs and risks associated with digital transformation and increase the willingness of enterprises to embrace digital transformation [29], promote the collaboration between various business practices, as well as effectively steer the incorporation and amalgamation of digital resources and technology into conventional industries, thereby facilitating their digital transformation. On the other hand, industrial digital transformation, particularly in domains such as design, production, supply chain management, and marketing models, fosters innovative industrial development, promoted the formation of innovation mechanisms and intensify innovation, create a product cost advantage in the industry, and in turn, spur industrial change [30]. Thus, the strategic deployment of digital policies lays the foundation for the establishment of an encompassing digital ecosystem, which becomes a crucible for innovation, efficiency, and resilience against external disturbances. This robust framework significantly fortifies the regional economy's ability to withstand the vagaries of external development uncertainties, enhancing its overall resilience.

As the new generation of information technology has the characteristics of strong permeability, high technology content and wide audience, the digital transformation of industry has obvious networking characteristics. Developing digital technology may bring about certain "silent costs" and "network effects" in the industrial digital transformation [31]. The combined force of the two means that at different stages, the impact of industrial digital transformation on regional economic resilience does not show an immutable linear characteristic.

Based on the above analysis of digital policies, industrial digital transformation, and urban economic resilience, hypotheses are proposed:

H2. The implementation of digital policies can promote urban economic resilience through industrial digital transformation.

H3. The impact of digital policies on urban economic resilience is influenced by industrial digital transformation in a nonlinear manner.

3.3. The role of environmental regulations

Environmental regulations are a series of environmental protection policies, regulations, and standards formulated and implemented by the government or relevant institutions, which affect the economic activities of cities in a variety of ways. On the one hand, strict environmental regulations will increase the cost of environmental impact assessment and transformation for enterprises in the early stage, squeeze out limited enterprise resources, and may thereby inhibit the intrinsic driving force of product innovation for enterprises [32]. At the same time, policy adjustments in environmental regulations will also increase market uncertainty to some extent, which in turn discourages innovation [33], thereby hedging or even inhibiting the effect of cities using digital policies to promote local industrial development; On the other hand, with the continuous promotion of environmental regulations, the elimination of backward production capacity and high pollution backward enterprises has been accelerated, guiding enterprises to transform their development concepts and methods [34]. Meanwhile, regulators can incentivize or require companies to disclose ESG information and performance through environmental regulations, thereby encouraging companies to adopt sustainable business practices [35], promoting green technology innovation activities, establishing first mover advantages in the market, strengthening the positive promotion effect of urban digital policies on industrial development, and thereby enhancing the resilience of urban economy.

In summary, the research hypothesis is proposed:

H4. Environmental regulation plays a moderating role with a U-shaped effect on this impact.

Based on the above research hypotheses, construct the theoretical hypothesis model of this article, as shown in Fig. 2.

4. Research design

4.1. Model design

Firstly, the Hausman test results obtained by the statistical software Stata 17 showed that the statistical value was 26.59 and the P value was 0.0030, and the fixed effect model should be used for estimation. Meanwhile, to alleviate endogeneity issues and reduce "selectivity bias", the following model is constructed using a double difference propensity score method (PSM-DID):

$$eco_{i,t} = \beta_0 + \beta_1 treated_{i,t} + \gamma Control_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

Among them, the dependent variable $eco_{i,t}$ in equation (1) represents the economic resilience of the province i in the year t; The core explanatory variable $treated_{i,t}$ represents the dummy variable of whether digital policies are implemented; $Control_{i,t}$ represents a series of control variables, λ_i represents fixed effects for provinces, μ_t represents fixed effects for years, $\varepsilon_{i,t}$ is a random error. When β_1 is statistically significant, which means that the p-value is less than 0.01, 0.05, or 0.1, and the coefficient is positive(negative), it indicates that digital policies significantly improve (reduce) the economic resilience of cities.

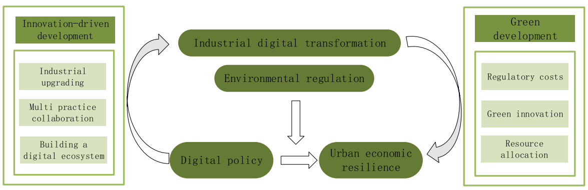

Fig. 2. Theoretical hypothesis model.

4.2. Variable selection

4.2.1. Explained variable

Selecting urban economic resilience(eco) as the dependent variable for this study. Due to data availability constraints, this article refers to the research methods of Yu et al. (2018) to conceptualize urban economic resilience through a three-part framework, including resistance and recovery, adaptation and regulation, as well as innovation and transformation [36]. In Table 1, specific indicator explanations are provided for the entropy weight method of comprehensive measurement.

4.2.2. Core explanatory variables

Digital Policy(*treated*). This article takes the value of 1 for provinces in China that have already released digital policies and 0 for the other provinces in China that have not, based on the timing of the release of digital policies in each province in China, as the interaction term of this article.

4.2.3. Moderating variables

Environmental regulation(*er*) is the moderating variable of this article. Here are two main ways to measure the level of environmental regulation: the single indicator method and the comprehensive index method. The single indicator method only considers a single indicator when measuring the intensity of environmental regulations. For example, the ratio of industrial pollution control costs to industrial output, pollution control expenditures and the ratio of investment in environmental pollution control in each province in China to local GDP to measure environmental regulation [37–39]; The comprehensive index method considers a weighted combination of multiple indicators when measuring environmental regulations to generate a comprehensive index or score. For example, the industrial wastewater discharge compliance rate, industrial sulfur dioxide discharge compliance rate, industrial dust discharge compliance rate, and industrial solid waste comprehensive utilization rate are used to comprehensively measure the intensity of environmental regulations [40] and environmental protection expenditures, abatement costs, taxes to measure environmental regulatory intensity [41]. This paper draw upon the study of Wang et al. (2021) and optimize it to construct an environmental regulation evaluation index [42]. The specific structure is as follows:

$$er_{i,t} = \frac{Cost_{i,t}}{Industrial_{i,t}}$$

Among them, $er_{i,t}$, $Cost_{i,t}$ and $Industrial_{i,t}$ respectively represent the environmental regulation intensity of the i province during the t period, the cost of industrial output pollution control (the proportion of completed industrial pollution control investment to industrial added value), and the proportion of industrial added value to GDP.

4.2.4. Mediating variables

In this article, digital transformation of industries(*digital*) acts as a mediating variable. Based on previous research, this study constructs an evaluation index system for industrial digitization transformation from three dimensions: digital equipment level, digital platform construction, and industrial digitization application. Each province's digital transformation degree is calculated by weighting the indicators based on the entropy method. The indicators are described in Table 2.

4.2.5. Control variables

To make the research results more reliable, this paper combines the studies of Suárez et al. (2016) [43], Wang and Wei (2021) [44] and selects industrial structure(*str*), government support(*gov*), infrastructure construction(*estate*), urban residents' quality of life(*area*),

Table 1
Urban economic resilience index system.

Target layer	Criterion layer	Specific indicators	Attribute	Indicator measurement methods	Weight
Urban economic resilience	Resistance and Resilience	Level of economic development	Positive	Per Capita GDP	0.0997
		Economic growth	Positive	GDP growth rate	0.0082
		Price changes	Negative	Consumer Price Index for Residents	0.0272
		Income	Positive	Per capita disposable personal income	0.0977
		Self-financing	Positive	Local fiscal revenue/local fiscal expenditure	0.0645
	Adaptation and adjustment ability	Financial investment in education	Positive	Education expenditure/general public budget expenditure	0.0405
		Health capacity	Positive	Per capita number of beds in health institutions	0.1035
		Spending power	Positive	Total retail sales of social consumption/GDP	0.0257
		Income gap between urban and rural areas	Negative	Urban per capita disposable income/Rural per capita disposable income	0.0292
	Innovation and Transformation Power	R&D support level	Positive	The proportion of research expenditure to GDP	0.1424
		Urban education level	Positive	Number of faculty and staff in ordinary higher education institutions	0.0799
		Technology personnel	Positive	Full time equivalent of R&D personnel in industrial enterprises above designated size	0.2817

Table 2
Index system for industrial digital transformation.

Index	Indicator measurement methods	Attribute	Weight
Digital equipment level	Internet broadband access port	Positive	0.1331
	Mobile phone penetration rate	Positive	0.0632
	Mobile phone base station	Positive	0.1294
Digital platform construction	Number of computers used by enterprises per 100 people	Positive	0.0973
	Number of websites owned by every hundred enterprises	Positive	0.0252
	R&D investment/industrial added value of industrial enterprises above designated size	Positive	0.0983
Industrial digital applications	Revenue from express delivery business	Positive	0.4536

wage level(*salary*), regional economic prosperity level(*consumer*), human capital(*people*), economic development level(*pergdp*), and scientific and technological level(*tech*) as control variables. Specific variable descriptions and descriptive statistics are shown in Table 3.

4.3. Sample selection and data sources

Due to the lack of data in Hong Kong, Macao, Taiwan and Xizang, this paper selects 30 provinces in China from 2013 to 2022 as research samples, and the data sources are China Statistical Yearbook, China Environmental Statistical Yearbook, EPS database, China Economic Database and Chinese government website. Among them, the data on digital policies was manually organized by the author. This article conducted keyword searches ("digital economy", "platform economy", "artificial intelligence", "blockchain", etc.) on the provincial government websites of China. If the policy text of that year contains the above keywords, this paper believe that the province implemented digital policies in that year.

5. Empirical results and analysis

5.1. PSM matching results

To eliminate the problem of selection bias and to ensure the accuracy of the DID analysis, this study first conduct a PSM to 30 cities. Matching variables should be those that affecting the economic resilience of the city. This study contains nine matching variables: industrial structure(*str*), government support(*gov*), real estate development level(*estate*), urban resident quality of life(*area*), wage level (*salary*), regional economic prosperity level(*consume*), human capital(*people*), economic development level(*pergdp*), and scientific and technological level(*tech*). Using a 1-to-1 nearest neighbor matching method, the matched samples are obtained, And a balance test was

Table 3
Explanation of research variables and descriptive statistics.

Variable type	Variable	Variable Symbol	Calculation method	Mean value	standard deviation
Explained variable	Urban economic resilience	*eco*	see above	0.290	0.149
Core explanatory variables	Economic policy	*treated*		–	–
Mediating variables	Industrial digital transformation	*digital*		0.198	0.137
Adjusting variables	Environmental regulation	*er*		0.089	0.101
Control variable	Industrial structure	*str*	The proportion of primary industry × 1+the proportion of secondary industry × 2+the proportion of the tertiary industry × 3	2.388	0.123
	Government support	*gov*	The proportion of general budget expenditure of local finance to GDP	0.231	0.110
	Infrastructure construction	*estate*	Logarithm of urban residential investment	7.641	0.898
	Quality of urban residents	*area*	Per capita green space area	13.394	2.762
	Salary level	*salary*	Average salary of employees	11.204	0.322
	Regional economic prosperity level	*consumer*	Logarithm of the total retail sales of consumer goods in society	9.127	0.956
	Human capital	*people*	The proportion of students in higher education institutions to the total population at the end of the year	0.012	0.004
	Level of economic development	*pergdp*	Logarithm of Per capita GDP	10.927	0.425
	Scientific and technological level	*tech*	Logarithm of technology expenditure	4.354	1.057

conducted on the matched samples. According to the findings presented in Table 4, the bias of the estimates after matching all variables is significantly reduced to 14 %, which meets the criterion of not exceeding 20 % [45], and the p-value is not significant, indicating that there is no significant difference between the treatment group and the control group after matching, so the matching results meet the requirements.

To test the matching effect of PSM, this article drew a probability distribution density function graph of propensity score values to verify the matching effect, as shown in Fig. 3. The graphs can clearly show that the probability density distributions of the matched control group and experimental group are closer to the samples before matching, indicating good matching effect. This further verifies the applicability and reliability of using PSM-DID for quantitative analysis in this article.

5.2. DID regression results

On the basis of the matched samples, regression analysis was conducted using model (1), and the estimated results are presented in Table 5. In column (1), this study control for time and solid effects and do not introduce any control variables. The regression coefficient for the core explanatory variable (treatment) is positive at the 1 % level of significance. In column (2), this study introduces control variables while still accounting for both time and solid effects. The regression coefficient for the core explanatory variable (treated) remains positive at the 1 % level of significance. This indicates that the implementation of digital policies has significantly promoted the enhancement of urban economic resilience, and hypothesis 1 has been validated.

In the analyses of this study, the results also revealed that five indicators, namely industrial structure (str), real estate development level (estate), urban resident quality of life (area), regional economic prosperity level (consumer) and scientific and technological level (tech) are all significantly positive, suggesting that they can contribute to the resilience of the urban economy in conjunction with digital policies. However, it is worth noting that government support (gov) and human capital (people), two indicators that are usually considered as key factors in enhancing economic resilience [46], show a negative relationship in this study's model, which actually diminishes the resilience of the urban economy. This finding may reflect unequal resource allocation, inadequate policy implementation, or inappropriate timing and method of government intervention, resulting in government support not working as effectively as expected. At the same time, although cities have a large pool of labor resources, the positive effect of human capital on economic resilience may also be weakened if the skills and knowledge of these resources do not match the needs of economic development, or if the education and training system fails to adequately enhance the professional and innovative capabilities of the labor force. This suggests that, in promoting government support and a greater role for human capital, we need to consider more carefully the rational allocation of resources, the effective implementation of policies and the optimization of education and training systems to ensure that these factors can truly contribute to the resilience of urban economies.

5.3. Robustness testing

5.3.1. Parallel trend test

One pivotal assumption of the DID method is the common trend, which requires that there should be parallel trends in urban economic resilience before and after the implementation of numerical policies. To preliminarily test the assumption, this paper utilizes the research method employed by Shi et al. (2018) to conduct parallel trend testing [47]. By using interaction terms, five dummy variables are established for regression analysis. These variables take on a value of 1 in the year before policy implementation and 2 years before policy implementation, and a value of 1 in the year of policy implementation, 1 year after policy implementation, and 2

Table 4
PSM balance test results.

Variable	Sample	Mean value		Deviation rate(%)	Reduce deviation rate(%)	T-test	
		Treated	Control			T	p>|t|
str	Before	2.4428	2.3675	64.6	96.4	5.54	0.000
	After	2.4253	2.4281	−2.3		−0.11	0.910
gov	Before	0.23499	0.27245	−26.3	85.2	−2.24	0.026
	After	0.262	0.25779	3.9		0.22	0.830
estate	Before	7.7913	7.3868	45.9	93.0	3.97	0.000
	After	7.6907	7.6625	3.2		0.17	0.869
area	Before	14.442	13.174	47.0	70.2	4.05	0.000
	After	13.843	14.221	−14.0		−0.70	0.486
salary	Before	11.454	11.006	191.8	98.9	16.47	0.000
	After	11.275	11.27	2.1		0.15	0.883
consumer	Before	9.2081	8.8597	36.9	88.2	3.18	0.002
	After	9.0765	9.1175	−4.4		−0.23	0.822
people	Before	0.01407	0.1216	44.8	92.7	3.87	0.000
	After	0.01329	0.01343	−3.3		−0.13	0.897
pergdp	Before	11.184	10.819	94.9	98.7	8.17	0.000
	After	11.001	10.996	1.3		0.06	0.951
tech	Before	4.832	4.2572	55.8	90.9	4.85	0.000
	After	4.6532	4.6008	5.1		0.25	0.803

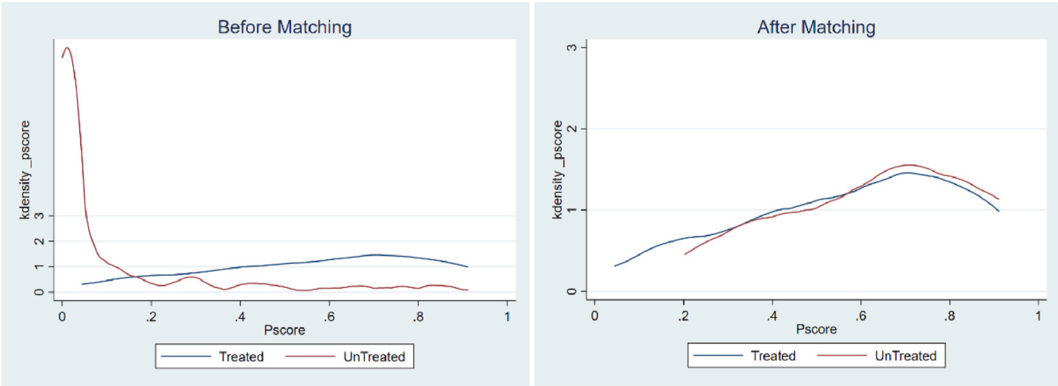

Fig. 3. Probability distribution density function of propensity score values.

Table 5
Regression results of digital economy strategy on urban economic resilience.

Variable	(1)	(2)
	eco	Eco
treated	0.027***	0.023***
	(0.0085)	(0.0050)
str		0.092*
		(0.0500)
gov		−0.130***
		(0.0466)
estate		0.010*
		(0.0060)
area		0.003***
		(0.0011)
salary		0.047
		(0.0391)
consumer		0.041***
		(0.0132)
people		−4.325*
		(2.2589)
pergdp		−0.006
		(0.0220)
tech		0.051***
		(0.0051)
Constant	0.234***	−1.021**
	(0.0036)	(0.4549)
Year-fixed	control	control
City-fixed	control	control
R^2	0.5700	0.8716
N	208	208

Note: *p < 0.1**P < 0.05***P < 0.01; Standard error in parentheses; Same as below.

years after policy implementation. The results presented in Table 6 indicate that the coefficients of the dummy variables before the official implementation of the policy are not statistically significant, suggesting that the double difference model used in this study aligns with the parallel trend hypothesis. On the other hand, the coefficients of the dummy variables in the year of policy implementation and subsequent years are statistically significant, indicating that digital policies have a lasting impact on urban economic resilience post-implementation.

Table 6
Parallel trend test.

	P value
pre2	0.923
pre1	0.495
cur	0.002
af1	0.027
af2	0.002

Here, this study shows the estimated coefficients of regression and the associated 95 % confidence intervals for the interaction term to better demonstrate the test results. It is clear from Fig. 4 that that the regression coefficients before policy implementation are not statistically significant, but show significant statistical significance in the year of policy implementation and subsequent years. In summary, the double difference model used in this paper is consistent with the parallel trend assumption and proves the robustness of the findings of this paper.

5.3.2. Placebo test

Considering that the improvement of urban economic resilience may be influenced by other policies and factors, in order to eliminate such interference, this paper chooses to conduct random sampling, repeat 500 times, and draw a kernel density distribution map of the estimated coefficients. In Fig. 5, the estimated coefficients follow a normal distribution and are close to zero, which is consistent with the expectations of the placebo test, indicating the study's findings are reliable.

5.3.3. Replacement matching method

This article uses 1-on-1 nearest neighbor matching for PSM matching, and now changes to kernel matching to perform robustness testing on the paired samples. The regression results after matching are shown in Table 7, and the coefficients of treated are still significantly positive, indicating that the results of this article are not affected by the PSM matching method and remain robust after changing the method.

5.4. Regional heterogeneity analysis

Given the disparities in social environments, resource endowments, and other contextual factors, policy implementation effectiveness often varies across different regions. To discern these differences between inland areas and developed coastal regions, our study further investigates regional heterogeneity by dividing China into these two categories. Table 8 presents the regression results for both regions. Interestingly, only the interaction coefficient in column (1) is significantly positive, indicating that digital policies have significantly improved the economic resilience of cities in China's coastal areas; However, contrary to our initial expectations, the interaction coefficient in column (2) is positive but not significant, indicating that digital policies have not significantly improved the urban economic resilience of the region in inland China. These results shed light on the nuanced impact of policy interventions across diverse geographical contexts and the observed disparities in policy effectiveness can be attributed to several factors. In most inland areas, local governments grapple with limited fiscal capacity, restricted policy levers, and a scarcity of tools to foster resilient urban economic development, especially incentive policy tools, resulting in the weaker infrastructure, technology, and talent. Consequently, the impact of digital policies on urban economic resilience remains modest in these regions. Conversely, China's coastal areas, characterized by economic prosperity and high-tech industrial clusters, exhibit a different landscape. These regions boast ample government financial resources, a well-structured industrial base, abundant scientific and technological innovation elements, and comprehensive infrastructure. As a result, digital policies have a pronounced positive effect on the economic resilience of cities along the coast, which may further expand the regional gap among cities across the country.

6. Further analysis: Mechanism testing

6.1. Mediation effect

According to the previous analysis, as an industrial practice of digital policy, industrial digital transformation may have an intermediary effect in the process of digital policy affecting urban economic resilience. In order to test the existence of this effect, this

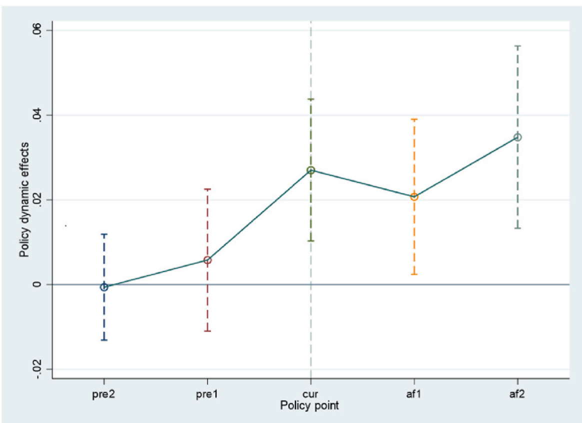

Fig. 4. Visualization of parallel trend test.

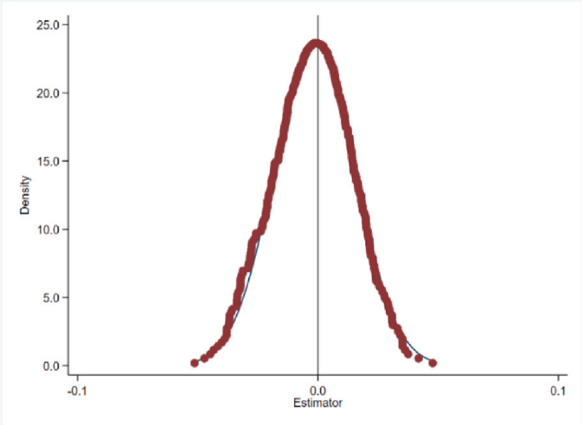

Fig. 5. Placebo test.

Table 7
Robustness test.

Variable	Kernel matching
	eco
treated	0.016***
	(0.0059)
str	0.028
	(0.0502)
gov	−0.100*
	(0.0538)
estate	0.020***
	(0.0069)
area	0.003**
	(0.0013)
salary	0.070
	(0.0459)
consumer	0.038***
	(0.0143)
people	−7.185***
	(2.5113)
pergdp	−0.014
	(0.0254)
tech	0.053***
	(0.0060)
Constant	−1.051**
	(0.5278)
Time effect	control
Individual effect	control
R^2	0.8468
N	224

Table 8
Regional heterogeneity analysis.

Variable	(1)	(2)
	Coastal areas	Inland areas
	eco	Eco
treated	0.041**	0.016
	(0.1682)	(0.0124)
Constant	0.323***	0.185***
	(0.0068)	(0.0042)
Year-fixed	control	control
City-fixed	control	control
R^2	0.4553	0.6592
N	73	135

article draws on the research results of Song et al. (2024) [48] and constructs the following mediating effect model:

$$eco_{i,t} = \alpha_0 + \alpha_1 treated_{i,t} + \gamma Control_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{2}$$

$$digital_{i,t} = \alpha_0 + \alpha_2 treated_{i,t} + \gamma Control_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{3}$$

$$eco_{i,t} = \alpha_0 + \alpha_3 treated_{i,t} + \alpha_4 digital_{i,t} + \gamma Control_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{4}$$

Among them, equations (2)–(4) verify the mediating effect of industrial digital transformation(digital) on the relationship between digital policies and urban economic resilience. If the impact coefficients α_1, α_2, α_3 and α_4 are significant, then industrial digital transformation plays a mediating role.

The mediation effect results are presented in Table 9. In column (1), the regression coefficient for *treated* is 0.057, which is statistically significant at the 1 % level. Similarly, in column (2), the coefficient is 0.104, also significant at the 1 % level. This suggests that the implementation of digital policies can foster industrial digital transformation. When this study includes industrial digital transformation as a mediator variable in column (3), the regression coefficients for *treated* and *digital* become 0.008 and 0.477, respectively. These coefficients are significant at the 10 % and 1 % levels, indicating that industrial digital transformation plays a mediating role between digital policy and urban economic resilience. In essence, the implementation of digital policies effectively guides the allocation of digital resources and promotes the digital transformation of various industries. Moreover, the digital transformation of traditional industries contributes to the development of a robust digital application ecosystem, which in turn promotes the growth of advanced industries, enhances innovation capabilities, and ultimately strengthens the ability of regional economies to withstand external uncertainties. So hypothesis 2 can be proven.

6.2. *Threshold effect based on industrial digital transformation*

The previous text has verified that under the transmission mechanism of industrial digital transformation, digital policies do indeed enhance urban economic resilience. However, differences in the development level of industrial digitalization inevitably leads to differences in resource matching. At the same time, due to the "network effect" of information technology, the degree of industrial digitization also plays a different role in the digital policy process, affecting the economic resilience of cities. Based on the above analysis, the role of industrial digital transformation during this period is obviously non-linear. Therefore, this article intends to use threshold regression models to further discuss this non-linear effect.

To provide an in-depth explanation of the potential threshold characteristics for industrial digital transformation, this article analyzes them from two perspectives: national, coastal and inland regions. Firstly, the threshold variables were tested for threshold effects. The specific results are shown in Table 10. When industrial digital transformation is used as the threshold variable, the P-values of both the national and two major regions are significant and through the dual-threshold model. In other words, there are dual thresholds for the impact of national digital policies on urban economic elasticity from an overall perspective and the thresholds are 0.2452 and 0.5450 respectively; From a regional perspective, there are dual thresholds for the impact of digitalization measures in coastal and inland areas on urban economic elasticity, the thresholds are 0.3823, 0.6463 and 0.1804, 2487 respectively. Therefore, in this study, dual thresholds are chosen for further estimation and industrial digital transformation is classified as low, medium and high based on the thresholds.

The regression results are presented in Table 11. Initially, when the degree of digital transformation in industries remains low, the coefficient representing the impact of digital policies on the economic resilience of cities fails to achieve statistical significance. However, as the level of industrial digital transformation escalates from low to medium and high, the coefficients of digital policy on urban economic elasticity are 0.042 and 0.092 respectively, both significant at the 1 % level. In other words, as the digital transformation of industries increases, the influence of digital policies on urban economies also increases. The positive promoting effect of elasticity gradually appears, showing an increasingly obvious strengthening trend. The underlying reason for this trend may be due to the insufficient integration of advanced technologies such as digital and information into the production, operation, and sales of traditional industries at a low level of industrial digital transformation, resulting in a low level of industrial digitization, which hinders the effective guidance of digital policies on digital resources; as the industrial digitization improves, it leads to diversified business

Table 9
Analysis of mediation effect mechanism.

Variable	(1)	(2)	(3)
	eco	digital	eco
treated	0.057***	0.104***	0.008*
	(0.0041)	(0.0063)	(0.0039)
digital			0.477***
			(0.0238)
Constant	0.265***	0.152***	0.190***
	(0.0027)	(0.0041)	(0.0045)
Year-fixed	control	control	control
City-fixed	control	control	control
R^2	0.4263	0.5070	0.7372

Table 10
Threshold effect test and estimation results.

Threshold variable	Region	Threshold number	P value	BS frequency	Estimated value	95 % confidence interval
Industrial digital transformation	nationwide	single	0.0000	300	0.2452	[0.2428,0.2544]
		Double	0.0000	300	0.5450	[0.4741,0.6060]
	coastal	single	0.0000	300	0.3823	[0.3599,0.3982]
		Double	0.0167	300	0.6463	[0.6218,0.7265
	Inland	single	0.0000	300	0.1804	[0.1774,0.1828]
		Double	0.0400	300	0.2487	[0.2355,0.2605]

Table 11
Threshold effect regression results.

Threshold features	Nationwide	Coastal areas	Inland areas
Digital interval	digital<0.2452	digital<0.3823	digital<0.1804
Treated	−0.009	−0.004	−0.013**
Digital interval	0.2452≤digital≤0.5450	0.3823≤digital≤0.6463	0.1804≤digital≤0.2487
Treated	0.042***	0.061***	0.011*
Digital interval	digital>0.5450	digital>0.6463	digital>0.2487
Treated	0.092***	0.100**	0.052***
Control variable	control	control	control
Constant term	−0.973***	−1.024***	−0.884***
R^2	0.8214	0.8166	08625

models and new industrial forms, and enhances the level of industrial upgrading. Moreover, advanced digital technologies also improve the information interaction and sharing capabilities, and the coordination of regional and departmental information interaction, which in turn enhances the resilience of urban economy.

According to regional variations, the impact of digital policies on urban economic resilience is not significant when the digital transformation of coastal industries is low. However, when the digital transformation of coastal industries reaches a medium to high level, digital policies have a significant positive effect on urban economic resilience, showing a marginally increasing non-linear characteristic that aligns with the national development trend. On the contrary, when the digital transformation of inland industries is low, digital policies have a negative impact on urban economic resilience. However, when the degree of digital transformation of inland industries reaches a medium to high level, digital policies have coefficients of 0.011 and 0.05 respectively, both of which are significant. This indicates a significant positive effect and a marginal increasing non-linear characteristic. The regional difference in the impact of digital policies on urban economic resilience may be attributed to the fact that most inland areas serve as gathering areas for traditional Chinese industries. When the digital transformation of industries is at a low level, the support of new generation information technology for physical industries is weak, resulting in high costs of enterprise information exchange, low integration of various innovative factors, and weak synergy among different links in the industrial chain. As a result, the improvement of urban economic resilience is suppressed. However, with the advancement of industrial digitalization, the new generation of information technology can effectively integrate and penetrate into various industries. This integration can effectively reduce information transmission costs, break down 'information silos', strengthen data sharing and cooperation among different links in the industrial chain, and enhance the stability of the urban economic system in the face of external environmental uncertainty. From the above analysis, it can be concluded that hypothesis 3 has been validated.

6.3. Regulatory effects

According to previous analyses, environmental regulations may have a moderating effect on the impact of digital policies on urban economic resilience. To test the existence of this effect, this article draws on the research results of Fairchild and MacKinnon (2009) [49] and constructs a moderating effect model:

$$eco_{i,t} = \omega_0 + \omega_1 treated_{i,t} + \omega_2 er_{i,t} + \gamma Control_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{5}$$

$$eco_{i,t} = \omega_0 + \omega_3 treated_{i,t} + \omega_4 er_{i,t} + \omega_5 treated_{i,t} {}^* er_{i,t} + \omega_6 treated_{i,t} {}^* er_{i,t}^2 + \gamma Control_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{6}$$

Among them, equations (5) and (6) test the moderating effect of environmental regulation (er).The testing process is as follows: after incorporating ***er*** variables, the coefficient of the independent variable(ω_1) is significant; Lastly, after incorporating the interaction between the independent variable and environmental regulation, as well as the interaction between the independent variable and environmental regulation squared, if the interaction coefficient ω_5 and ω_6 in equation (6) is still significant, then the moderating effect is valid.

The results of the moderating effect are shown in Table 12. Column (1) shows that the coefficient of the core explanatory variable (*treated*) is significantly positive, satisfying the first condition; After including the interaction term in column (2), the core explanatory variable still plays a significant positive role, but the coefficient of the interaction term $treated_{i,t} {}^* er_{i,t}$ is −1.026 and significant, indicating that environmental regulations have played a significant negative regulatory role, that is, environmental regulations will to some extent inhibit the effect of digital policies on urban economic resilience. Therefore, the qualification restrictions and reviews brought about by strict environmental regulations increase the implicit costs of enterprises. Simultaneously, investments in technology, capital, equipment, and other resources to meet high environmental standards alter the resource allocation structure of businesses, potentially reducing their focus on product innovation and research and development. Consequently, enterprise digital transformations may suffer, weakening the overall effects of digital policies on urban economic resilience; The coefficient of the interaction term $treated_{i,t}*er_{i,t}^2$ is 3.966 and significant, indicating that environmental regulations have played a significant positive regulatory role. That is, with the advancement of environmental regulation, the marginal costs associated with pollution control decrease, which encourages enterprises to conduct green technological innovation under the influence of environmental regulation. This continuous innovation creates a long-term "innovation compensation" effect, which offsets or even reverses the negative effect of the costs caused by environmental regulations during the early stages of implementation.

In summary, the findings suggest that environmental regulation initially weakens the positive promotion effect of digital policy on urban economic resilience. However, once environmental regulation reaches a certain level, it strengthens this positive effect. Hypothesis 4 was confirmed.

7. Conclusions and policy implications

7.1. Conclusions and discussions

Previous literature has emphasized the importance of economic factors such as economic output, income, and the business environment on the economic resilience of cities, but little attention has been paid to the impact of policy factors on the economic resilience of cities, and even less to digital policies. The paper has verified the academic speculations of the previous article through relevant data collection (provincial panel data for China from 2013 to 2022) and reasonable methodological use (PSM-DID model), and indirectly verified that the findings of the authors of the previous supporting literature are indeed reasonable. Therefore, compared with other studies, on the one hand, the article has a certain practical significance, and the intrinsic relevance of digital policymaking and the resilience of urban economic development is a major issue of concern for major economies to achieve sustainable development in the era of digital economy. Our findings show that digital policies have positively influenced urban economic resilience, and this finding remains robust after conducting various tests. On the other hand, it uses a more cutting-edge policy evaluation methodology, and makes some improvements in the introduction of economic resilience factors and the comprehensiveness of empirical data, and its conclusions are more in line with China's actual situation. Our results that the influence of digital policy on urban economic resilience is found to be non-linear and varies with the degree of industrial digitalization. Additionally, environmental regulation is identified as playing a dynamic regulatory role in the nexus between digital policies and urban economic resilience. At the same time the impact of digital policy implementation on regional economic resilience varies significantly due to different factor endowments across regions.

While this study provides valuable insights, it's pertinent to recognize its limitations. Firstly, the data employed in this research are somewhat limited in terms of both scope and geographical reach. Consequently, the conclusions derived from this analysis might be applicable only to specific regions, thereby constraining their wider relevance. This limitation underscores the necessity for caution in extending these findings to other contexts or scenarios. Secondly, this investigation predominantly explores the effects of two intermediary variables—environmental regulation and industrial digital transformation—on the relationship between digital policy and urban economic resilience. It's crucial to acknowledge, however, that urban economic resilience is shaped by a complex array of factors. By concentrating on just a select few of these elements, the study may have overlooked other variables that could significantly influence urban economic resilience. This omission suggests that the study's conclusions represent just a segment of a broader, more intricate landscape. Future research endeavors could benefit from incorporating a wider range of variables, which might reveal more nuanced insights into how digital policies can bolster urban economic resilience.

Table 12
Analysis of regulatory effect mechanism.

Variable	(1)	(2)
treated	0.027***	0.066***
	(0.0085)	(0.0127)
er	−0.007	−0.009
	(0.0197)	(0.0188)
treated*er		−1.026***
		(0.2860)
treated*er^2		3.966**
		(1.5822)
Constant	0.235***	0.235***
	(0.0043)	(0.0042)
Year-fixed	control	control
City-fixed	control	control
N	208	208
R^2	0.5703	0.6170

7.2. Policy implications

Based on the above conclusions and discussions, the empirical analysis in this article provides policy makers some implications:

(1) Promote the interaction and integration between digital technology and the real economy, and expand the promoting effect of industrial digital transformation on economic resilience. On the one hand, various regions should increase investment and construction in data centers and data trading platforms, improve digital access capabilities and network coverage, narrow the digital divide, while strengthening digital transformation and guidance for traditional industries, promoting a number of digital solutions and demonstration projects, and enhancing the intelligence, networking, and flexibility level of traditional industries; On the other hand, various regions should increase investment and support in digital technology research and development, promote the integration of digital technology and the real economy, and thus, build an industrial innovation system based on a group of digital technology innovation platforms with international competitiveness.

The government should increase investment in the research of new generation information technology, and encourage universities, enterprises, and governments to form artificial intelligence technology innovation research alliances. For urban areas with good economic foundations, it is necessary to strengthen the application of artificial intelligence technology in the fields of economic development monitoring, early warning, and resource allocation involved in urban development. By promoting urban innovation capabilities, regional economic resilience can be improved. For rural or underdeveloped areas, emphasis should be placed on promoting digital infrastructure construction, enhancing the awareness of local governments and residents about the use of artificial intelligence, and using artificial intelligence to promote the transformation and development of traditional manufacturing industries in underdeveloped areas, ultimately enhancing the economic resilience of rural areas. Of course, for the use of artificial intelligence technology, attention should also be paid to its potential social risks, and local governments should establish strict laws, regulations, and industry development standards.

(2) Enhance the effectiveness of environmental regulations by identifying the development status of industries. It is important for the government to conduct more research on local industries and grasp the economic status of local industries. Several steps can be taken to reduce the costs of enterprise digital construction in the early stages of digital transformation, such as increasing the support of green funds for industry, reducing various costs of enterprise digital construction and enhancing the willingness of enterprises to undergo digital transformation. For industries with a certain digital foundation, support and rewards for green technology innovation in enterprises should be increased through financial subsidies, tax incentives, credit convenience, intellectual property protection, and other means to stimulate the internal innovation momentum of enterprises and promote the improvement of regional economic resilience.
(3) Develop differentiated digital policies based on the endowment of regional innovation factors. For regions with poor innovation factor endowments, emphasis should be placed on strengthening digital and intelligent infrastructure construction, and improving the hardware foundation for industrial digital transformation. For regions with good innovation factor endowments, we should strengthen the construction of digital governance, digital supervision and other systems, optimize the construction of digital innovation systems, and enhance the promoting effect of digital policies on regional economic resilience.

CRediT authorship contribution statement

Yang Zheng: Writing – original draft, Software, Formal analysis, Data curation. **Wei Chen:** Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Wandan Zou:** Validation, Resources, Investigation.

Data availability

The labeled datasets used to support the finding of this study are available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors gratefully acknowledge the support provided by the national social science foundation (Grant No. 22XJY040).

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