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Impact of industry-university-research collaboration and convergence on economic development: Evidence from chengdu-chongqing economic circle in China

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ABSTRACT

Collaboration among industry, universities, and research is crucial for building an innovative nation. Although industry-university-research collaborative innovation (IURCI) and time-space convergence can drive innovation, increase productivity, and spur economic development, their effects on the regional economy have not been thoroughly examined in existing literature. Therefore, this study investigates the impact of industry-university-research collaborative innovation (IURCI) and time-space convergence on economic development in China. Specifically, we focus on local-level cities in the Chengdu-Chongqing Economic Circle (CCEC) and construct an evaluation index system and time-space convergence model to measure the effects of IURCI and time-space convergence on economic development from 2007 to 2021. Our findings indicate that the efficacy of IURCI on economic development in China follows an inverted U-shaped curve, meaning that the marginal impact of IURC may decrease as more creative funds are deployed. Furthermore, the positive marginal effect of inventive talent input may decrease when it surpasses a certain value in an open innovation environment. The spatiotemporal convergence of collaborative innovation and development levels of IURCI in the CCEC shows significant differences. Regionally, the development level of IURCI in different regions exhibits significant differences in state and speed of convergence. In the southern Sichuan urban agglomeration, the collaborative innovation level of industry, education, and research follows an evolutionary process from convergence to divergence and then to convergence. Policymakers should pay close attention to the spatial effect of high-level development of regional IURCI and promote regions with higher development to drive regions with relatively weak development levels.

1. Introduction

Innovation is a main driving factor for development and a crucial strategy for countries worldwide. Within the framework of an innovation-driven development strategy, industry-university-research collaborative innovation (IURCI) plays an important role [1]. The effective development of IURCI promotes resource integration and close collaboration between enterprises, universities, research

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institutes, and other innovation subjects, facilitating coordinated development that has an important and far-reaching impact on regional economic growth and scientific and technological progress [2]. IURCI has become a new organizational model for innovative countries and regions seeking to improve independent innovation capabilities and establish multi-subject joint innovation. Innovation is a main factor of economic development and a critical component of a nation's ability to compete internationally [3]. China, the world's second-largest economy, has made significant strides in investing in self-governing innovation, research, and development. Its academic accomplishments and patents are among the highest in the world. However, despite these advancements, China's innovation process still lags behind in bridging the gap between its economy and technology. IURCI and time-space convergence (TSC) can encourage economic growth and innovation [4]. Combining their unique capabilities, these factors generate new possibilities and stimulate growth.

The term "time-space convergence" refers to the phenomenon of diminishing differences in economic performance and living standards between regions and countries over time [5]. It refers to the idea that economic progress and development are spreading globally, resulting in a convergence of income levels and standards of living among various countries and areas [6]. Multiple factors, including the development of technology, globalization, and the expansion of international trade and investment, contribute to TSC [7]. As technology and information are shared internationally, it becomes easier for less developed nations to catch up to more developed nations in terms of economic performance and living standards. This can lead to a decrease in income and living standard gaps across regions and countries [8]. TSC is essential for policymakers and economists since it can guide discussions regarding the most effective tactics for increasing economic growth and eliminating poverty and inequality [9]. The combined effort of IURCI and TSC can provide interdisciplinary research and innovation, entrepreneurship, skills development, regional economic development, and global competitiveness. Although previous research has focused on these concepts individually, we combined them to explore their real impact on economic development in China.

Contemporary scientific and technological innovation has broken through the traditional linear model of the innovation value chain due to the increasing complexity and speed of technological innovation and the continuous development of the global economy [10]. This evolution has resulted in a model that is nonlinear, networked, multi-role, and open. The collaborative interaction of multiple subjects has become the basis of this innovative model. IURCI is a complex innovation organization method that breaks down innovation barriers and creates an innovative community of mutual assistance, cooperation, and mutual benefit based on core elements such as universities, enterprises, and scientific research institutions [11]. Scholars have suggested that IURCI can facilitate knowledge interaction [12,13] and resource complementarity between industry, universities, and research institutes by involving various subjects [11,14–17]. In the collaborative innovation mechanism of industry-university-research (IUR), universities and research institutes serve as the knowledge output end, while industries act as the knowledge input end. The process of knowledge flow is utilized to enhance industrial innovation performance by applying knowledge effectively to all aspects of industrial innovation activities.

The industry can provide scientific research funding support for universities and research institutes and offer research thinking and inspiration from the perspective of enterprises, which promotes the innovation [18]. Collaborative innovation from the perspective of IUR cooperation emphasizes the construction of the IURCI system from an overall perspective, which promotes the formation of a multi-faceted, multi-level, and triple helix network cooperation structure of IUR cooperation. This structure enhances creativity, improves invention ability, and promotes knowledge creation [19]. IUR cooperation from the perspective of collaborative innovation emphasizes the collaboration and mutual assistance of all parties involved in industry, academia, and research, and promotes the long-term sustainable creation of knowledge to enhance innovation efficiency [15]. As a result, IURCI has become a significant research topic for academia, industry, and government departments.

The urban agglomeration in the Chengdu-Chongqing Economic Circle (CCEC) is considered a significant player in China's urban and economic growth [20]. It is also recognized as a center for innovation. The CCEC is a major urban agglomeration located in the upper part of the Yangtze River Basin [21], which is developed as a crucial component of economic growth strategy of China. The CCEC is also a significant economic growth pole in the inland and non-coastal area [22]. This study has selected CCGE due to its crucial role in the regional economy.

Some previous studies already dealt with the impact of IUR collaboration on various regions, including European countries [23], Australia [24], US, Japan and Korea [25], and US, Germany, and France [26], others focused on specific countries like China [17,27,28], Turkey [29], Italy [30], Brazil [18,31], and the UK [32]. Previous studies focused on either university–industry collaboration [18,19,31,33–35], and university-industry-government collaboration [11,12,14,15,36–38] or economic convergence [6,39–47], there are limited studies that have focused on the combined effect of these concepts. Therefore, this study aims to address three research questions: (a) How does IURCI impact the regional economy? (b) How do TSC effects impact the regional economy? And (c) What is the combined effect of IURCI and TSC on the regional economy in China?

While existing studies provide significant references for this study, there is still scope for expansion. First, most research has concentrated on the national or provincial level and lacks spatial scale aimed at the city level. Second, research has focused more on the comparative analysis of the differences in development levels between large regions and less on the coordination of high-quality progress levels within urban agglomerations. Third, study on the spatiotemporal features of development is not in-depth enough, and more of it stays on the analysis of spatial correlations and less use spatial empirical models to test the spatial spillover impact of collaborative innovation and economic development. Therefore, this study takes the local-level cities of the CCEC as a case, develops an evaluation index to assess the IURCI condition, and puts forward targeted countermeasures and suggestions by measuring and analyzing the impact of TSC. This study adopts a comprehensive framework for analyzing the dynamics of economic convergence in the CCEC by combining the IURCI development levels with TSC modelling. This analytical framework explores the complex connections between collaborative innovation and regional economic development. As a result, it has the potential to generate valuable

insights that can inform policy development and strategic decision-making. This study offers a policy decision-making recommendation for further promoting the high-quality development of the CCEC and other areas with similar socio-economic features.

2. Literature review

2.1. Industry-university-research collaboration (IURC) and convergence

A dynamic synergy between industries, universities, and research institutions promotes economic growth within regions and drives collective innovation [18]. IURC is an embodiment of the Triple Helix paradigm [48], which highlights the interdependence of government, business, and academia in fostering innovation and knowledge transfer. The process of idea development, trial, and commercialization are dynamic and iterative, marking a shift from the conventional linear model of innovation [49]. Contrarily, convergence—which takes into account both temporal and geographical aspects—is a key concept in regional economic growth. Spatial convergence refers to the process through which economic differences across regions become less over time, while temporal convergence is the result of growth trajectories synchronizing across various locations [6].

Numerous scholars have made significant progress in the theory and practice of IURCI [50,51]. In 2003, American scholar Chesbrough introduced the concept of "open innovation" [49]. This approach systematically explores how to create new value by integrating internal and external innovation elements. Chesbrough believed that knowledge creation and diffusion, as well as the flow of senior talents, are happening at an increasingly rapid pace. Etzkowita and Zhou's "Triple Helix" [48] further highlighted that industry-university cooperation is the "third mission" of universities, along with teaching and research. Strengthening multiple interactions is essential to enhance the efficiency of the national innovation system. Lee [52] pointed out that obtaining complementary research results, entering new technology fields, developing new products, approaching important university personnel, and improving academic research are the main motivations for enterprises to participate in industry-academia collaborative innovation. Universities can also benefit from cooperation by obtaining financial support from enterprises, promoting the pragmatism of research, and exploring new research areas [27].

2.2. Importance of IURC for economic growth

The previous studies related to IURC emphasize the significant role in driving economic development by facilitating the spread of information, the diffusion of technology, and the transfer of innovative ideas [53]. The synergistic involvement of universities, research institutes, and enterprises fosters a conducive environment for the generation and dissemination of innovative ideas and technology [54]. The IURC plays a crucial role in promoting the convergence of scholarly research and industrial demands, so bolstering the process of transforming research findings into marketable goods and services [23]. This relationship fosters the creation of an innovation ecosystem, whereby the exchange of knowledge encourages entrepreneurial activities, improves competitiveness, and contributes to the economic growth of the area [16]. The literature has shown that areas that implement strong IURC processes see a boost in economic development, a rise in employment opportunities, and an improvement in global competitiveness [31,35].

2.3. Spatial and temporal convergence

The theoretical constructs of spatial and temporal convergence provide helpful frameworks for comprehending the patterns of regional economic growth. According to the idea of spatial convergence, it is suggested that places characterized by lower beginning income levels have a tendency to undergo more rapid economic development, resulting in a reduction of income inequalities across regions as time progresses [8,55]. Temporal convergence, however, pertains to the synchronization of economic growth rates across different areas, indicating the possibility of convergence in development paths [56,57]. These theories play a significant role in the analysis of economic differences and the identification of variables that either promote or impede regional convergence. Additionally, these findings provide valuable perspectives on the possible effect of the Indiana Utility Regulatory Commission (IURC) on the geographical and temporal dynamics of regional economic growth. This lens allows for an analysis of how collaborative innovation affects patterns of convergence.

2.4. Regional innovation systems

The previous literature on regional innovation systems (RIS) offers a complete comprehension of the intricate interrelationships among universities, research institutions, enterprises, and governmental agencies within a certain geographic area. The importance of local knowledge networks and collaborative partnerships in fostering innovation and achieving economic prosperity is emphasized by RIS [14]. The IURC framework highlights the significance of regional innovation systems in illustrating the interdependence between information generators and users. This interdependence facilitates the collaborative creation of value and the extensive dissemination of innovative ideas. The RIS theory offers valuable perspectives on how regions might strategically use their unique strengths and assets to promote the formation of innovation clusters, enhance knowledge sharing, and drive economic development [58]. The aforementioned concept has substantial significance in understanding the operational dynamics of the CCEC as a regional innovation system, whereby the integration of firms, colleges, and research institutes facilitates collaborative innovation and propels economic progress [59,60].

2.5. The case of chengdu-chongqing economic circle

The CCEC is taken as a case to analyze the complex dynamics that exist between the IURC and the promotion of regional economic development. The CCEC, situated in the southwestern part of China, encompasses a cluster of urban districts characterized by a diverse array of economic activities, institutions of higher education, and research facilities. The previously stated region has emerged as a robust economic entity, using its advantageous geographical location and effective institutional mechanisms, such as the IURC system, to foster innovation-driven growth [22]. The CCEC exhibits notable attributes, including its strategic geographic location, vibrant business ecosystem, and comprehensive development strategies. These factors make it an ideal setting for investigating the effects of IURC on spatial and temporal convergence, as well as its impact on regional economic outcomes [4]. Furthermore, the analysis of the CCEC case offers insightful insights into the policy interventions and strategies that promote effective collaboration among industries, universities, and research institutions, thereby enhancing economic progress within the designated geographical region [59].

Carayannis et al. [26] and Koschatzky [61] pointed out that improving collaborative innovation performance hinges on carefully considering the knowledge characteristics, and structure of cooperation, sharing knowledge, and the choice of knowledge transfer channels. Cluster innovation and new geoeconomics suggest that companies tend to collaborate and innovate with geographically close universities and research institutions [62]. Regarding the efficiency evaluation of IURCI, scholars have developed various collaboration evaluation models. Among them, the more representative models are the composite system collaboration model [36,63,64], coupled coordination degree model [63,65,66] and distance coordination degree model [67]. Scholars have also studied the synergy evaluation of the regional IURCI system [14,68], developed a variety of regional IURC evaluation models, and applied these models to quantitatively evaluate and compare the IURC in some provinces in China. For example, Zou and Zhu [69] reported that regional openness and research quality are crucial for the implementation of scientific innovation and the marketization of technology.

3. Materials and methods

3.1. Overview of the study area

The CCEC is situated in the Sichuan Basin of China, intersecting with the "Belt and Road" and the Yangtze River Economic Belt (as shown in Fig. 1). The CCEC covers a total area of 18.5 km^2 [70]. The scope of the region includes 15 cities in Sichuan Province, such as Chengdu, Zigong, and Luzhou, as well as the Chongqing area. As of 2019, the region's permanent population reached 96 million people, and the regional GDP was about 6.3 trillion yuan. In 2021, the State Council released the "CCEC Planning Outline," upgrading the construction of the CCEC, situated at the intersection of the upper reaches of the Yangtze River and the "Belt and Road," to a national strategy. This region is a key element in the domestic regional development pattern and carries the essential functions of factor agglomeration, economic radiation, and opening to the outside world. Therefore, promoting high-quality development of the

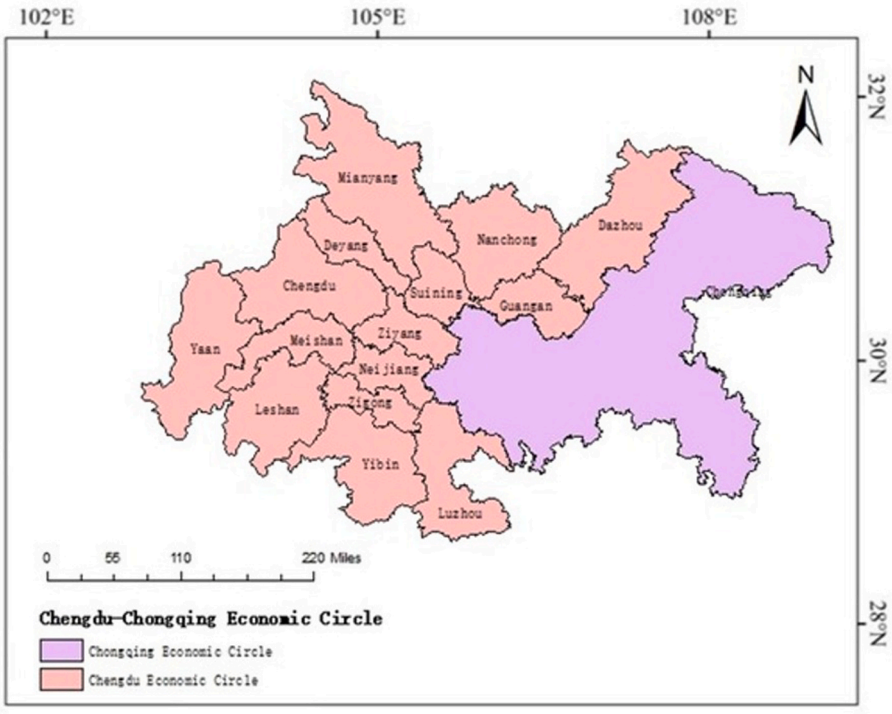

Fig. 1. Chengdu-Chongqing Economic Circle urban agglomeration.

CCEC is related to the significant strategy of forming a new model of regional economic development driven by urban agglomerations in China. This paper identifies the research's spatial scope, including 16 prefecture-level cities (Chongqing, Chengdu, Zigong, Mianyang, Luzhou, Leshan, Yibin, Suining, Nanchong, Dazhou, Meishan, Ziyang, Guang'an, Neijiang, Deyang, and Ya'an).

3.2. Index development and data sources

The IURCI comprises the collaboration of three major subsystems: enterprises, universities, and scientific research institutions. The universities and research institutes are mainly responsible for the function of knowledge creation, while enterprises are responsible for absorbing and applying innovative knowledge. Buesa et al. [71] reported that In the European region, innovation is primarily influenced by the researchers and the funding provided by the three main entities. These factors impact the investment in research and innovation. The number of patents filed per year by each entity is used as a tool to assess research output. Graf et al. [72], Cowan et al. [3], and Fritsch et al. [62] evaluated the role of research institutions, universities, and enterprise in collaborative innovation, respectively. They used indicators such as research personnel, expenditure, and cooperation contract turnover among various subjects as input variables. The output variables included the patent number, published papers, and new product income of enterprises. Moreover, the interaction between various entities cannot be separated but must have a close relationship, which can be examined from the perspective of knowledge interaction, such as technology market share, cooperative publications, and patent number.

The coupling coordination of the IURCI system is a state in which enterprises, universities, and research institutions cooperate and assist each other in a nonlinear manner, mutually influencing and interacting with each other. This transition from disorder to order can fully reflect the innovation level and ability of the regional innovation system [13,38]. Based on reference to existing research [50], and combined with the five principles of comprehensiveness [73], comparability [74], scientificity [50], representativeness [75] and data availability [74], this study selected 21 indicators from the three major subjects of enterprises [18,51,76], universities [17,35,50] and scientific research institutions [14,38,77] to construct an evaluation index system for IURCI level in the CCEC (Table 1).

Regarding data sources, this study takes 16 cities in the CCEC as the research unit. The relevant data (from 2007 to 2021) are from the China Statistical Yearbook, China Science and Technology Statistical Yearbook, and the statistical yearbooks and bulletins of relevant cities. When some of the data are missing, linear interpolation is used to supplement the data. The timeframe from 2007 to 2021 was selected for our study to ensure a full examination of the long-term trends and dynamics pertaining to industry-university-research cooperation and convergence within the Chengdu-Chongqing Economic Circle. The Subprime crisis holds considerable importance as a global event with far-reaching economic consequences. However, the selected time frame enables to incorporate various economic cycles and stages of development, facilitating a more comprehensive comprehension of the dynamic connections between industry, universities, research institutions, and economic development.

Table 1
Evaluation index system of IURCI level in Chengdu-Chongqing Economic Circle.

System layer	Dimension layer	Metrics layer
Industry-university-research collaborative innovation system	Industry	Government funds in R&D expenditure of industrial enterprises (million yuan)
		Internal expenditure of R&D expenses of industrial enterprises (million yuan)
		Number of R&D projects in industrial enterprises
		Proportion of R&D project personnel in industrial enterprises in total employees (%)
		R&D project investment of industrial enterprises (10,000 yuan)
		Number of invention patents owned by industrial enterprises (pieces)
		Industrial enterprises, high-paying technology industry, proportion of main business income (%)
	University	Government funds in R&D expenditure of colleges and universities (million yuan)
		Internal expenditure of R&D funds of colleges and universities (million yuan)
		R&D projects in colleges and universities (Number)
		Proportion of R&D project personnel in colleges and universities (%)
		R&D project funding for colleges and universities (10,000 yuan)
		Number of invention patents owned by higher education institutions
		Scientific papers published by institutions of higher learning
	Research institution	Government funds in R&D expenditure of research and development institutions (million yuan)
		Expenses of R&D institutions (million yuan)
		R&D projects of R&D institutions (Number)
		R&D project personnel in R&D institutions as a proportion of total employees (%)
		R&D project funding for research and development institutions (10,000 yuan)
		Number of invention patents owned by R&D institutions
		Scientific papers published by research and development institutions

Sources: Authors' compilation

3.3. Methods

3.3.1. Entropy weight method

To reduce the impact of subjective factors, the study employed the objective entropy method as part of the comprehensive evaluation method. This method was used to assess the degree of discreteness of indicators and determine the weights of each index. The basic calculation steps were as follows.

① Calculate the weight of the value of the *i*th and *j*th indicator.

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{1}$$

② Calculate the entropy value of the item *j*

$$e_j = -\frac{1}{ln\ n} \sum_{i=1}^{n} P_{ij} ln\left(P_{ij}^{n}\right) \tag{2}$$

③ Calculate the variance coefficient for item *j*

$$g_i = 1 - e_i \tag{3}$$

④ Calculate the weight coefficient for each indicator

$$w_j = \frac{g_i}{\sum_{j=1}^{m} g_i}, j = 1, 2\ ,\ \ldots, m \tag{4}$$

3.3.2. Comprehensive evaluation index

The linear weighting method was used to compute the development of IURCI in the CCEC in China from 2007 to 2021. The comprehensive benefit evaluation functions of the three subsystems of enterprises, universities and research institutions (EUI) were as follows.

$$I = \sum_{j=1}^{m} W_j P_{ij} \tag{5}$$

Here, *i* is the number of prefecture-level cities, *j* corresponds to 7 indicators of the enterprise subsystem.

$$U = \sum_{j=1}^{m} W_j P_{ij} \tag{6}$$

Here, *i* is the number of prefecture-level cities, and *j* corresponds to the seven indicators of the university subsystem.

$$R = \sum_{j=1}^{m} W_j P_{ij} \tag{7}$$

Here, *i* is the number of prefecture-level cities, *j* corresponds to the 7 indicators of the subsystem of scientific research institutions.

$$T = \sum_{j=1}^{m} W_j P_{ij} \tag{8}$$

Here, *i* is the number of prefecture-level cities, *j* corresponds to the comprehensive evaluation of regional enterprises, universities, and scientific research institutions for comprehensive evaluation of the level of coupling coordinated development, a total of 21 indicators.

I, U, and R in the formula represent the comprehensive benefit values of the three subsystems of EUI, respectively. *i* is the number of prefecture-level cities. *j* is the indicator in each system. *Wj* is the weight of each index in the three systems. *Pij* is the normalized value of each index in region i in each system after dimensionless.

3.3.3. Coupling coordination degree model

The coupling coefficient model was used in physics [78] and generalized the multi-system coupling degree model. The coupling

degree of IURCI in the CCEC is represented as:

$$C = \left\{ \frac{I \times U \times R}{\left[\frac{I \times U \times R}{3}\right]^3} \right\}^{\frac{1}{3}} \tag{9}$$

The coupling degree is $0 \leq C \leq 1$, and the nearer C is to 1, the larger the coupling degree of each subsystem. While the degree of coupling can measure the strength of the interaction between each subsystem, it cannot demonstrate the level of coordinated development. Therefore, it is essential to incorporate the coupling degree formula to evaluate the degree of mutual coordination between EUI. The formula is as follows:

$$D = \sqrt{C \times T} \tag{10}$$

where, D represents the degree of coupling coordination of the three systems.

3.3.4. Space-time convergence model

An econometric model of economic convergence was constructed based on the neoclassical growth model. Drawing on existing research [38,79,80], a spatial convergence model was constructed considering the time factor, and used to explore the convergence of the development level of IURCI in the Chengdu-Chongqing Economic Circle. In this study, the spatial convergence model considering time factors was referred to as the space-time β convergence model. This model can reflect the dependence of the sample area on time and space perspectives.

The convergence models from the time perspective are:

$$\frac{1}{T-t} log\left(\frac{y_{iT}}{y_{it}}\right) = \varphi - \left[\frac{1 - e^{-\beta(T-t)}}{T-t}\right] log(y_{it}) + \mu_{it} \tag{11}$$

If only the time span is one period *(T-t= 1)*, equation (8) can be expressed as: $log\left(\frac{y_{i,t+1}}{y_{it}}\right) = \varphi - (1 - e^{-\beta}) log(y_{it}) + \mu_{it}$ (12)

Among them, the subscript i (i = 1,2 … … … ….., n) represents the research unit, t. t represents the beginning and end of the research period. *T-t* represents the time span, and the collaborative innovation development level of *t* and *T* period, respectively.

$log\left(\frac{y_{iT}}{y_{it}}\right)$ represents the logarithmic growth rate of the collaborative innovation development level in the *T* period. The parameter β indicates the convergence speed, which is constant, indicating that the model satisfies the random error term of the classical assumption.

Let, $r_{i,\,t+1} = log\left(\frac{y_{i,t+1}}{y_{it}}\right)$, $r_{i,\,t+1}$ is a first-order logarithmic growth rate, use the spatial weights matrix *W* to obtain the first-order spatial logarithmic growth rate, $r_{t+1} = log\left(\frac{y_{i,t+1}}{Wy_t}\right)$.

Transform the convergence model from the time perspective into the convergence model in the spatial perspective, and represent it in the form of a matrix.

$$r_{t+1} = \varphi - \left(1 - e^{-\beta}\right) log(Wy_t) + \mu_t \tag{13}$$

Where, y_t represents the vector spatially formed by the observations of the sample area in the Wy_t period, which is the average of the sample observations according to the characteristics of the spatial weight matrix.

Multiplying both ends of formula (13) to the left by the space weight matrix W and then subtracting formula (13) itself, we get:

$$(I - W) r_{t+1} = (I - W)\varphi - \left(1 - e^{-\beta}\right)(I - W) log(Wy_t) + (I - W)\mu_t \tag{14}$$

Therefore , I is the identity matrix; then, $\varnothing = (I - W)\varphi$, $\varepsilon_t = (I - W)\mu_t$, get,

$$(I - W) r_{t+1} = \varnothing - \left(1 - e^{-\beta}\right)(I - W) log(Wy_t) + \varepsilon_t \tag{15}$$

Equation (15) is a spatiotemporal β convergence model, which reflects the spatial relationship between the gap in the development level of IURCI and the gap in the corresponding growth rate. If the parameter β is greater than zero, the development level of collaborative innovation is in a state of spatiotemporal convergence. The larger β value encourages the convergence speed [59,81]. Conversely, if the parameter β is less than zero, the development level of collaborative innovation is in a state of spatiotemporal divergence [82].

The statistical analysis was performed using SPSS 23 and Microsoft Excel to thoroughly evaluate the links and dynamics that underlie industry-university-research cooperation (IURC) and convergence within the CCEC. A comprehensive assessment framework was established by calculating many indices, convergence parameters, and graphical representations. We used SPSS 23 software for the purpose of data processing and conducting sophisticated statistical analyses, therefore assuring a thorough investigation into the statistical significance of the data. The use of Microsoft Excel facilitated the production of instructive graphs and figures, so enhancing the clarity and visual comprehension of our results.

Table 2
Measurement of IURCI level in Chengdu-Chongqing Economic Circle.

Area	2007				2011	
	Industrial enterprises	Institutions of higher learning	Research institutions	Coupling coordination	Industrial enterprises	Institutions of higher learning
Chongqing	0.385	0.396	0.388	0.699	0.492	0.456
Chengdu	0.537	0.599	0.477	0.603	0.609	0.655
Zigong	0.196	0.161	0.201	0.236	0.262	0.204
Mianyang	0.326	0.312	0.312	0.470	0.283	0.396
Luzhou	0.253	0.285	0.232	0.310	0.258	0.225
Leshan	0.326	0.269	0.233	0.251	0.335	0.243
Yibin	0.208	0.218	0.237	0.214	0.229	0.277
Suining	0.318	0.236	0.201	0.249	0.289	0.300
Nanchong	0.266	0.282	0.167	0.305	0.282	0.277
Dazhou	0.201	0.178	0.168	0.253	0.241	0.212
Meishan	0.385	0.419	0.345	0.451	0.332	0.388
Ziyang	0.325	0.118	0.187	0.200	0.369	0.150
Guang'an	0.212	0.165	0.235	0.254	0.272	0.179
Neijiang	0.298	0.173	0.168	0.321	0.311	0.169
Deyang	0.317	0.217	0.277	0.206	0.328	0.176
Ya'an	0.234	0.288	0.212	0.107	0.267	0.366

4. Results and discussion

This section diligently addresses the research questions by presenting the findings and their implications. This study confirms that the IURC framework and convergence played pivotal roles in driving economic growth and regional development within the CCEC.

4.1. Analysis of IURCI and chengdu-chongqing economic circle development

The comprehensive benefit values of the three major subsystems, namely enterprises, universities, and scientific research institutions, were calculated based on the weights of their respective indicators using Equations (5)–(7). The coupling coordination degree of the IURCI system was determined using formula (10), and the evaluation results are shown in Table 2.

From a time series perspective, the levels of industrial, university, and scientific research development in 16 cities showed a steady upward trend from 2007 to 2021. Among them, the development level of the industrial system was slightly higher than that of the university system, and the development level of the university and scientific research institution systems were comparable. The development level of the industrial system showed a downward trend between 2011 and 2017, followed by a sharp increase in 2019. The system of scientific research institutions showed a trend of an increasing folded line "W". The level of coupling coordination also showed a trend of first rising, then falling, and then rising again. Zhang et al. [63] reported that the coupling coordination degree between the economic efficiency of urban land use and the level of green manufacturing system in the Chengdu-Chongqing Economic Circle was seen to be in a phase of gradual expansion. However, from 2019 to 2021, the overall coupling coordination decreased slightly. These results indicate that with strong state support to the western region, the development level of industry, education, and research has steadily improved. Nevertheless, the phenomenon of uneven development has become increasingly prominent, resulting in significant differences in the development of cities in the region [21].

From a spatial sequence perspective, the degree of collaboration of IURCI systems in various regions differs, and there are apparent regional characteristics. The development level of Chengdu and Chongqing was significantly higher than that of other regions in terms of the four indicators of industry, universities, scientific research, and the industry-university-research coupling coordination level. Both cities showed a steady improvement trend. This implies that these urban areas have been demonstrating advancements in their collective innovation endeavors and economic growth. The differentiation between the two levels was more pronounced. It indicates that while both cities had positive growth trends, Chongqing saw a comparatively more accelerated and substantial advancement in contrast to Chengdu. The variation in rates of development may be ascribed to a multitude of reasons, including divergent policies, distribution of resources, influx of investment, specialization in industries, and ability for innovation. This also implies that Chengdu and Chongqing are rapidly attracting talent to gather as the two major centers in the Chengdu-Chongqing urban agglomeration (CCUA). Liu et al. [4] argued that CCUA plays a crucial role in bolstering the economic development of the southwestern region of China but also has a noteworthy influence on the nation's endeavors in international collaboration. Moreover, the population quality, industrial structure, and scale are more reasonable in Chengdu and Chongqing, and the economic development level ranks first. The government attaches great importance to the deep integration of industry, universities, and scientific research to promote economic and social development.

In terms of industrial development, the development level of Chongqing is significantly higher than the overall development level, while the development level of the Chengdu plain urban agglomeration (CPUA) is comparable to the overall level, and slightly higher than the overall level after 2011. As shown in Table 2, Chengdu and Chongqing are the two cores of the CCUA, but the development level of the CPUA is lower than that of Chongqing, indicating a lower level of development in the CPUA, except for the seven cities near

2011		2016				2021			
Research institutions	Coupling coordination	Industrial enterprises	Institutions of higher learning	Research institutions	Coupling coordination	Industrial enterprises	Institutions of higher learning	Research institutions	Coupling coordination
0.461	0.753	0.552	0.523	0.512	0.777	0.554	0.536	0.556	0.865
0.522	0.680	0.623	0.676	0.567	0.715	0.717	0.698	0.628	0.791
0.287	0.275	0.285	0.229	0.315	0.238	0.282	0.293	0.387	0.316
0.362	0.422	0.315	0.412	0.358	0.435	0.353	0.423	0.421	0.450
0.239	0.376	0.269	0.252	0.264	0.384	0.313	0.329	0.336	0.381
0.301	0.274	0.328	0.245	0.322	0.284	0.354	0.314	0.356	0.322
0.288	0.284	0.256	0.310	0.356	0.342	0.319	0.397	0.456	0.413
0.268	0.262	0.299	0.255	0.324	0.268	0.336	0.289	0.373	0.274
0.256	0.296	0.276	0.301	0.298	0.314	0.313	0.328	0.312	0.357
0.208	0.321	0.268	0.224	0.256	0.301	0.271	0.254	0.289	0.357
0.389	0.502	0.389	0.419	0.421	0.503	0.431	0.402	0.419	0.550
0.214	0.230	0.366	0.168	0.268	0.251	0.382	0.223	0.288	0.277
0.268	0.251	0.256	0.171	0.276	0.305	0.281	0.219	0.328	0.343
0.171	0.357	0.308	0.189	0.195	0.336	0.323	0.242	0.245	0.380
0.281	0.256	0.367	0.197	0.309	0.331	0.345	0.217	0.328	0.337
0.236	0.124	0.278	0.311	0.256	0.135	0.311	0.398	0.294	0.156

Source: Authors' estimation

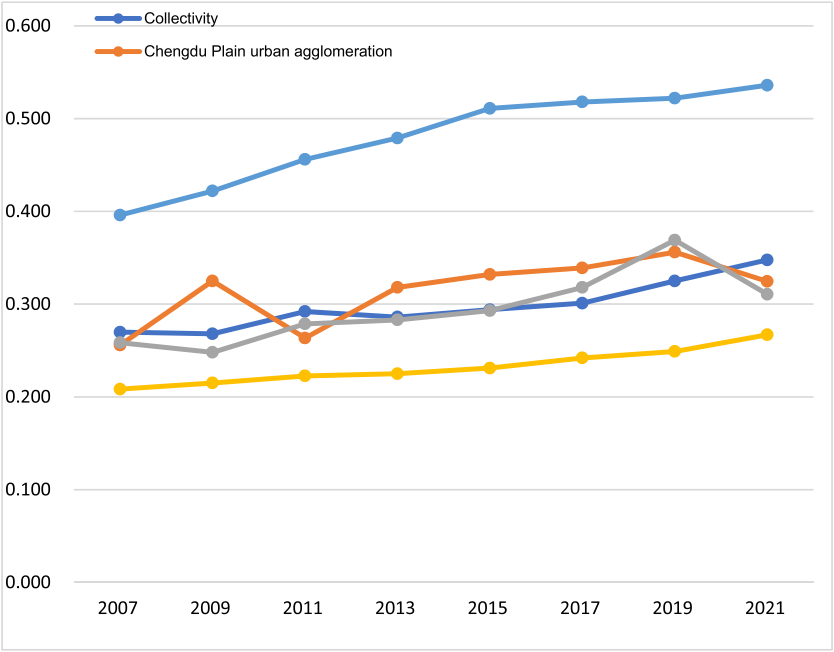

Fig. 2. Development level of industry system of CCEC.
Source: Authors' estimation

Chengdu, and a more pronounced two-level differentiation. The development level of the southern Sichuan urban agglomeration (SSUA) and the northeastern Sichuan urban agglomeration (NSUA) is slightly lower than the overall level, and peaked in 2011 before showing a downward trend until 2017, after which it began to recover. The development level of the NSUA is slightly lower than that of the SSUA, but the development trend is consistent (see Fig. 2).

Regarding the development level of colleges and universities, Chongqing has a much higher level of development than the overall average. Meanwhile, the urban agglomeration in the Chengdu Plain has a slightly higher level of development than the overall average. The urban agglomeration in southern Sichuan is basically consistent with the overall level, while the development level of the urban agglomeration in northeast Sichuan is relatively the lowest. These results indicate that with the implementation of strategies such as the CCEC, Chengdu and Chongqing play a pivotal role in the field of education, with more high-level universities and research institutions in terms of both quantity and quality than in other regions [83]. Additionally, Ziyang City, located on the main axis of

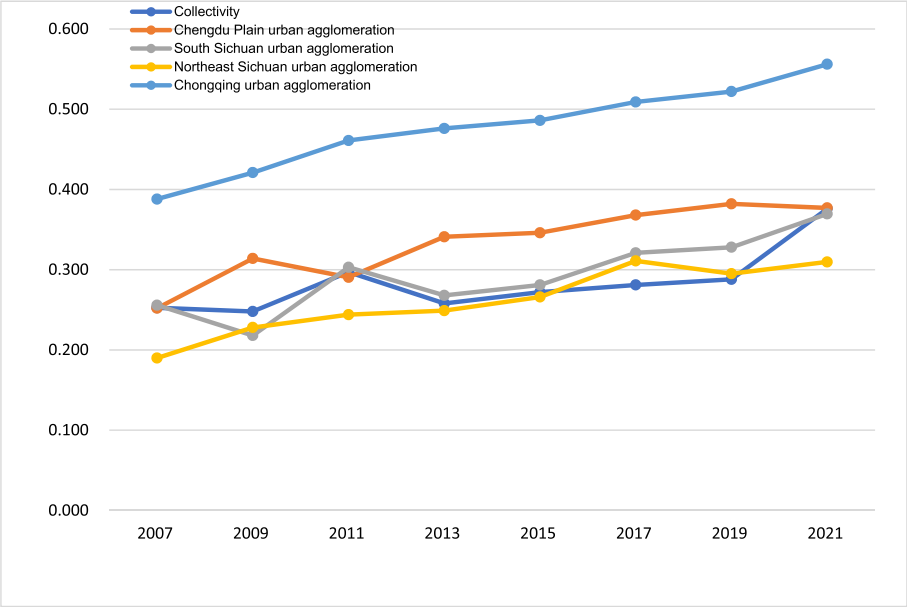

Fig. 3. Development level of university system in CCEC.
Source: Authors' estimation

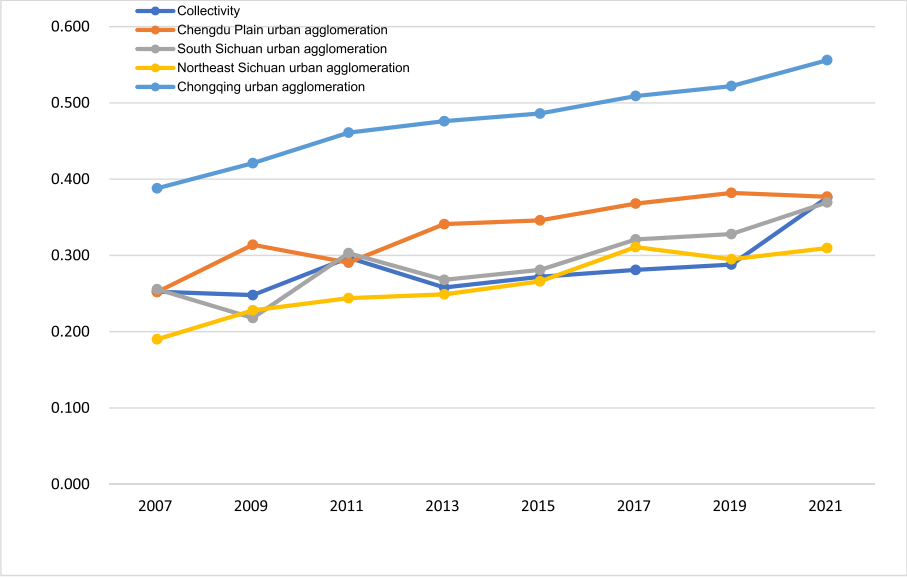

Fig. 4. Development level of research institution system in CCEC.
Source: Authors' estimation

development between Chengdu and Chongqing, has seen rapid growth. The densely populated urban areas in southern Sichuan, centered around Zigong City and Neijiang City, have rich educational resources. Furthermore, the recent construction of Yibin University City has led to a rapid improvement in the development level of colleges and universities in southern Sichuan (see Fig. 3).

The development level of research institutions is similar to that of colleges and universities. Chongqing stands out with a much higher level than other regions, followed by the Chengdu Plain urban agglomeration, which has a slightly higher level than the overall average. Cui and Tang [60] argued that in order to enhance the degree of collaborative innovation inside the urban agglomeration, it is essential to develop specific policies or construct a cohesive organization. The urban agglomerations in southern and northeastern Sichuan, however, have relatively low levels of development. The urban agglomeration in southern Sichuan aligns with the overall average (Fig. 4).

The degree of coupling coordination in IURCI systems varies among regions and shows distinct regional characteristics. Chongqing

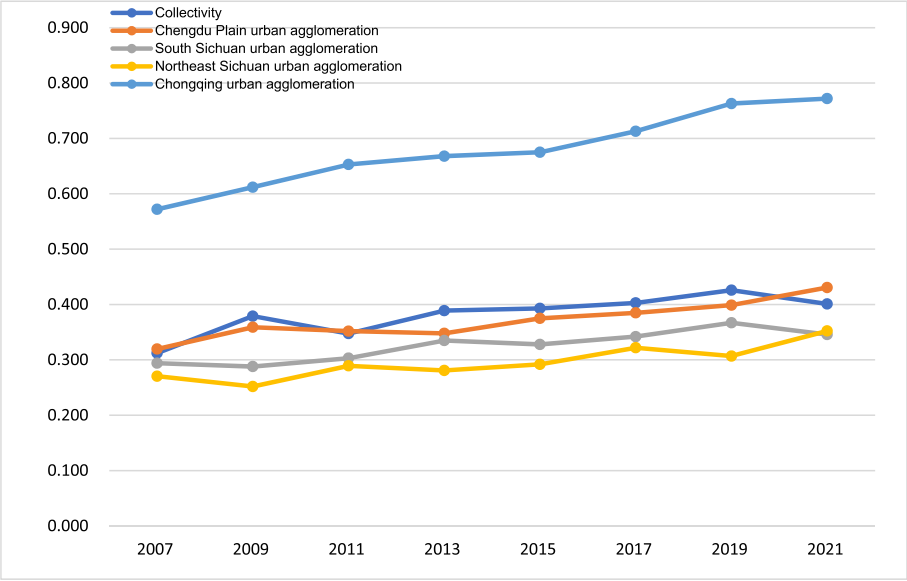

Fig. 5. Development level of IURCI system in CCEC.
Source: Authors' estimation

has a higher level of IURCI than other regions, while the urban agglomeration in the Chengdu Plain is similar to the overall average. The urban agglomeration in Northeast Sichuan has the lowest level of collaboration. Although the coupling coordination level in Chengdu is much higher than the overall average, the urban agglomeration in the Chengdu Plain has a similar level of coupling coordination. This suggests a large gap and serious polarization in the development of coupling coordination in the Chengdu plain area [4].

Overall, regions with higher levels of synergy in the IURCI system tend to be economically developed areas. From a macro-regional perspective, these areas have a strong economic foundation and advanced technology compared to underdeveloped areas. This provides financial support for IURCI and the technical conditions to overcome the "stuck neck" problem [84]. In terms of policy, economically developed areas belong to economic adjacency, and economically adjacent areas are more likely to produce positive spatial effects in the coordination of industrial development [85]. This can form a cluster structure and improve the efficiency of IURCI [29]. For underdeveloped regions, the synergy level of the IURCI system has significantly improved, mainly due to the enhancement of national economic strength and the strong financial and policy support provided by the national government through the western strategy. This strategy has stimulated enterprises' investment in underdeveloped areas, increased the number and scale of innovation subjects in regional IURCI, and provided more opportunities for IURCI (Fig. 5).

4.2. *Time-space convergence of chengdu-chongqing economic circle*

Temporal and spatial changes are two key evaluation dimensions that significantly affect economic development. The main way to measure regional differences in development and identify the factors that influence their change at different stages is to analyze the evolution and development process of spatial differences. This study introduces a spatial geographic distance matrix based on latitude and longitude distance, establishes a spatiotemporal β convergence model, and combines the IUR-CI development level value in the Chengdu-Chongqing region from 2007 to 2021 with equation (15) to conduct a β parameter estimation study. The study divides the time into three periods: the recovery period, rapid development period, and new normal period of high-quality development of China's economy after the crisis, which are 2007–2011, 2012–2016, and 2017–2021 respectively. A spatiotemporal analysis model is then constructed to illustrate the temporal and spatial convergence of high-quality economic development.

Overall, the IURCI level of the Chengdu-Chongqing economic circle shows a significant spatiotemporal β convergence. The β coefficient value of each short time is greater than 0, indicating that during the inspection period, the development of IURCI in the CCEC has been in a state of convergence. This means that there is a large gap between areas with a higher level of development (i.e., the central area) and areas with a lower level of development (i.e., the peripheral area) during the inspection period, and the development speed of the central area is lower than that of the peripheral areas. However, in the next period, the gap in the level of development tends to gradually decrease, and there is a phenomenon of catching up from underdeveloped areas to developed areas. The β coefficient has increased year by year from 2007 to 2021, with the estimated value of the parameter in 2017–2021 being the largest. This indicates that the degree of convergence has shown a rapid increase trend since entering a new age of high-quality development. Coordinated development policies and measures have achieved remarkable results. Liu et al. [60] argued that in order to enhance the centrality indices of national-level big urban areas in the Chengdu-Chongqing region, it becomes imperative to facilitate the spatial concentration of various elements and optimize the advantages derived from agglomeration economies.

Table 3
Estimation of spatiotemporal convergence parameters for the development of IURCI.

Parameters		2007–2011			2012–2016			2017–2021		
		β	-(1-$e^{-\beta}$)	Intercept	β	-(1-$e^{-\beta}$)	Intercept	β	-(1-$e^{-\beta}$)	Intercept
Collectivity (Including Chongqing)	Estimates	0.004	0.003	−1.49E-03	0.007	−0.010	2.23E-07	0.011	0.013	3.12E-05
	T	–	1.912	−0.245	–	−3.491	0.625	–	−3.732	0.126
Chengdu plain urban agglomeration	Estimates	0.004	0.036	−6.57E-04	0.008	0.586	3.22E-05	0.009	−0.376	2.18E-05
	T	–	−3.241	0.125	–	2.675	0.223	–	−4.135	−0.441
Chuannan urban agglomeration	Estimates	0.006	−0.019	2.12E-06	−0.002	−0.365	−4.15E-06	0.014	−0.258	3.24E-06
	T	–	−3.728	0.499	–	−1.262	0.324	–	−4.521	−0.239
Northeast Sichuan urban agglomeration	Estimates	0.006	−0.016	−4.41E-05	0.008	−0.024	5.21E-04	0.011	−0.158	2.19E-05
	T	–	−2.125	0.423	–	−3.146	0.366	–	−1.863	0.213

Source: Authors' estimation

When looking at the development level of IURCI across different regions, it becomes clear that there are significant differences in both the state and speed of convergence. For instance, during the 2012–2016 period, the β value of the Chengdu Plain urban agglomeration was greater than the overall level, indicating that the region was experiencing strong development momentum. The surrounding cities were able to achieve good progress under the leadership of Chengdu's absolute core. However, between 2017 and 2021, the β value of the Chengdu Plain urban agglomeration was lower than the overall level, suggesting that Chengdu's central city's driving role in peripheral cities had weakened. This could be due to several factors, such as excessive concentration of talents in cities, technical and intellectual resources, environmental protection measures, and the elimination of backward production capacity.

On the other hand, the collaborative innovation level of industry, education, and research in the southern Sichuan urban agglomeration followed an evolutionary process from convergence to divergence and back to convergence. During 2007–2011, it showed a state of convergence. However, during 2012–2016, the value of β was less than 0, indicating a state of divergence. From 2017 to 2021, it once again showed a state of convergence, with a value of β as high as 0.014, much higher than the overall level of the same period. This shows that although the southern Sichuan region had a single industrial structure, less talent inflow, and insufficient motivation for technological innovation between 2012 and 2016, the convergence characteristics became very obvious after entering the new normal of economic growth. This was achieved by improving the level of opening up to the outside world and vigorously developing Yibin University City and Industrial Park. These measures effectively formed a synergistic role in regional development and had a positive and significant radiation function (Table 3).

Note: According to the "Twelfth Five-Year Plan for Urbanization Development of Sichuan Province" and the "New Urbanization Plan of Sichuan Province (2014–202)", the urban agglomeration of the Chengdu Plain in this article includes: 8 cities: Chengdu, Mianyang, Deyang, Leshan, Suining, Ya'an, Ziyang and Meishan; The urban agglomeration in northeast Sichuan includes: Nanchong, Guang'an and Dazhou 3 cities; The southern Sichuan urban agglomeration includes: Yibin, Luzhou, Zigong and Neijiang 4 cities. The entropy measure's negative value, denoted as −1 Σ, indicates a deviation from ideal equilibrium or optimum coordination amongst the subsystems of industry, university, and research institutions. In the present context, a negative entropy value signifies a scenario whereby the coupling coordination among the IURC subsystems is below the optimal level, perhaps suggesting the presence of inefficiencies or imbalances in their interactions.

The development level of IURCI in the northeast Sichuan urban agglomeration converged significantly in all three periods, with the convergence speed increasing with each period [86]. The convergence speed in each period was also faster than the overall level [87]. This shows that the development level of underdeveloped areas will become closer and closer to that of developed areas. Due to past lagging economic, scientific, and educational development in northeast Sichuan, the economic radiation effect of the central region in the peripheral areas is significant. By ensuring full utilization of the "spillover effect" of developed areas and their latecomer advantages and learning from experience and lessons in development through the way of "learning by doing," the coordinated development of regional production, education, and research can be promoted [88]. This will gradually narrow the development gap with developed regions.

4.3. Policy recommendations

This study suggests the following recommendations based on the results.

First, the authority should engage the meta-governance function of government departments in overall planning and coordination, and adhere to the combination of central coordination and local responsibility. Similarly, central government departments should strengthen the top-level design and macro-governance of the collaborative innovation and development of industry-university-research institutes. The central government should formulate a flexible and unified regulation and guidance system, conduct macro-governance of Chengdu-Chongqing IURCI development in accordance with the law, and adjust the interests of all governance subjects. They should also work to dispel the "segmentation" pattern that exists in the management system in the Chengdu-Chongqing region, ensuring the smooth progress of orderly cooperation among industries, universities, and scientific research institutions. This

will provide a favorable macro policy environment for the coordinated development of industry-university-research institutions in the Chengdu-Chongqing region. The local government of Chengdu-Chongqing should conscientiously implement policies and regulations while consulting and formulating a plan for the development of the vocational education cluster. They should carry out the overall design of the overall requirements, development principles, strategic positioning, and development goals of the development of the vocational education cluster in Chengdu-Chongqing area. This will promote the effective implementation of coordinated development measures such as cooperation between industries, universities, and scientific research institutions in running schools, resource sharing, teacher exchanges, and mutual recognition of credits.

Second, the authority should improve the coupling degree between the layout structure of vocational colleges in the CCEC and the distribution structure of the regional economy. The local government of Chengdu and Chongqing should make reasonable adjustments to the layout of colleges and vocational colleges in accordance with the regional economic development strategy and the distribution of high-tech industries. They should also establish vocational colleges suitable for leading regional industries properly in the core areas of emerging high-tech agglomeration, such as Deyang and Mianyang. Meanwhile, similar or the same type of vocational colleges that are densely distributed in Chengdu and Chongqing can be upgraded and reorganized by abolition, merger, etc. The layout planning of vocational colleges compatible with regional economic distribution should be promoted. Different vocational colleges in adjacent geographical areas require a gradual transition from point-to-point communication between colleges to line-to-line connections between vocational colleges and enterprises. Then, it forms a network distribution structure around regional industries and builds a layout of vocational colleges that empowers the development of local industries.

Third, the spatial effect of high-level development of regional IURCI should be emphasized during policy decisions to promote regions with higher development levels to drive regions with relatively weak development levels. It has been found that the development of IURCI has a very significant spatial correlation, and it is easier to realize the transfer and actively radiate the collaborative innovation in the surrounding areas driven by the high level of collaborative innovation development. Each region should fully understand its advantages and disadvantages, use each other's strengths in a targeted manner, and strive to achieve the balanced development of various subsystems. Each region can apply the IURCI collaboration evaluation system constructed in this study to help analyze the development status and characteristics of industry-university-research in cities and counties under the region's jurisdiction from top to bottom. Then it is necessary to build the innovation pole of the region from the bottom up to form a collaborative pool of regional IURCI so that the structure of the IURCI system in the region becomes more reasonable.

5. Conclusions

This study constructed an evaluation index approach for assessing the IURCI level and used the entropy weight method to measure the development level of IURCI in the Chengdu-Chongqing Economic Circle from 2007 to 2021. The study also used the spatiotemporal β convergence analysis model to assess the spatiotemporal convergence characteristics of the CCEC. Based on these analyses, this study draws the following conclusions.

Firstly, the development levels of IURCI in the 16 cities in the CCEC showed a steady upward trend from 2007 to 2021. The level of coupling coordination also showed a U-shaped trend, initially rising, then falling, and then rising again.

Secondly, with regards to space, the degree of collaboration of IURCI systems in various regions varied, and there were distinct regional characteristics. Concerning the four indicators of industry, universities, scientific research, and industry-university-research coupling coordination level, the development level of Chengdu and Chongqing was much higher than that of other regions, and both showed a steady improvement trend. The two-level differentiation was clear, with the development level of Chongqing being much higher than the overall development level. The development level of the urban agglomeration of the Chengdu Plain was the same as the overall development level. The development level of the urban agglomeration in southern Sichuan and the urban agglomeration in northeast Sichuan was slightly lower than the overall level, but the development trend was essentially consistent. In terms of the development level of colleges and universities, the development level of Chongqing was much higher than the overall development level, whereas the development level of the urban agglomeration in the Chengdu Plain was slightly higher than the overall level. The urban agglomeration in southern Sichuan was basically consistent with the overall level, whereas the development level of the urban agglomeration in northeast Sichuan was relatively the lowest. In terms of the development level of research institutions, it was essentially similar to the development level of colleges and universities. Concerning the coupling coordination degree of IURCI, the level of IURCI in Chongqing was still higher than that in other regions. The urban agglomeration of the Chengdu was similar to the overall level, and the level of synergy in the northeast Sichuan urban agglomeration was the lowest.

Finally, concerning spatiotemporal convergence, the collaborative innovation and development level of IURCI in the CCEC showed significant differences. Overall, the development level of IURCI generally showed convergence characteristics during the research period. The regional speed of higher development level slowed down, whereas the development speed of regions with a lower development level accelerated. The gap between IURCI development levels in different regions continued to narrow with the passage of time. From a regional perspective, the convergence state and speed of IURCI development level differed significantly between different regions, and the convergence speed of the Chengdu Plain urban agglomeration continued to increase with the passage of time. The urban agglomeration in southern Sichuan showed the evolution process of convergence to divergence and then to convergence. The level of IURCI and development of the urban agglomeration in northeast Sichuan has converged significantly in three periods, and the overall convergence speed has increased.

This study provides significant insights into the relationship between IURCI and time-space convergence in the Chengdu-Chongqing Economic Circle. However, we recognize some constraints associated with this research. First, the use of retrospective data may have the potential to reduce the precision and comprehensiveness of the study. Second, the study's concentration on a

particular geographic location may restrict the applicability of its results to other areas characterized by other economic and developmental factors. Third, the inquiry predominantly focuses on macro-level governance and policy interventions, possibly neglecting the micro-level complexities that may impact IURCI and convergence outcomes. Fourth, the Subprime crisis holds considerable importance as a global event with far-reaching economic consequences. Future research should focus on examining the particular effects of this event on the variables and outcomes. Finally, it should be noted that this study did not thoroughly examine exogenous influences such as geopolitical developments or technological disruptions, which may have influenced the observed findings.

Future research should expand upon the comprehension of the intricate interplay between collaboration among industry, universities, and research institutions, convergence, and the advancement of economic growth. In order to overcome the constraints, a more extensive and dynamic dataset that encompasses many locations and a longer temporal scope might perhaps provide a more profound comprehension of the underlying mechanisms. A more detailed examination might investigate specific characteristics at the micro-level that either facilitate or impede the achievement of successful IURCI and convergence results. In addition, the utilization of qualitative research methodologies may be utilized to effectively capture the viewpoints of stakeholders, therefore offering a comprehensive understanding of the underlying dynamics. Furthermore, a thorough examination of the impact of emerging technologies, innovation ecosystems, and global economic trends on IURCI and convergence has the potential to augment the prognostic capability of models and provide practical insights for the development of policies. Future research should also attempt to incorporate a variety of academic viewpoints and investigate the intricate connections between IURCI, time-space convergence, and economic growth in various geographical settings.

Data availability

The data will be shared on request.

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CRediT authorship contribution statement

Hong Xiao: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Xuemei Cui:** Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Md Nazirul Islam Sarker:** Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **R.B. Radin Firdaus:** Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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.

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