



The diversity and Triple Helix interactions among universities, industries and governments: case of climate change field

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Abstract

The construction of an efficient national innovation system is beneficial to academic performance of institutes. Institutional diversity and Triple Helix (TH) interactions exhibit distinct characteristics in capturing relationships among universities, industries, and governments (UIG). They are correlated, complementing each other to present a comprehensive performance assessment of these entities. Taking the field of climate change as an example, this study combines micro-institutional collaboration analysis of contract-driven explicit interactions of UIG with macro-systemic evaluation of institutionally-guided implicit synergistic relationships. The participation of different institutions in the climate change research can be measured through the institutional diversity indicator, and the dynamic synergy effects can be explored through the TH indicators among different topics and countries. The results show that both institutional diversity and the synergy effect show initial increase followed by a subsequent decrease, but they are not synchronized. An increase (decrease) in the proportion of single-institutional publications weaken (enhance) the likelihood of various collaboration patterns, consequently eroding (promoting) the TH interactions. The decline in synergy effect is mainly associated with the gradual dominance of the proportion of publications from universities. There are minor disparities in the TH relationship among the different topics and countries because of various research content/national conditions. More diversified cooperation patterns need to be encouraged through relevant policies and practices.

Keywords Diversity · Triple Helix · Climate change · Collaboration · University-Industry–Government

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Introduction

In the era of innovation-driven development, university-industry-government (UIG) collaboration has emerged as an important strategy for enhancing national innovation capacity (Etzkowitz, 2002, 2003, 2011; Leydesdorff, 2003). A self-sustaining ecosystem for knowledge production, transfer, and transformation can be created by systematically integrating three dynamic forces from different entities: the needs of industrial practice, academic frontier exploration, and optimized governance solutions. This system can break through the boundaries of traditional innovation entities, promote the transition from basic research to applied technology through institutional coupling, and thereby optimize the efficiency of innovation resource allocation across society (Lavie & Drori, 2012; Schillebeeckx et al., 2016; Zhang et al., 2019). Consequently, comprehensively analyzing UIG interactions and tracking the dynamic evolution of collaborative benefits enables objective characterization of partnership patterns and intensity, establishing an empirical foundation for evidence-based policy interventions. Some exploratory studies have pioneered quantitative assessments of these domains through two different perspectives: micro-level institutional collaborative relationships and macro-level systemic synergies.

Institutional collaborative relationships

Research focusing on micro-level institutional collaborative relationships typically categorizes co-authorship publications or patents into seven groups: publications from single-institutions including universities (U), industries (I) or governments (G), and from cross-institutions (i.e., institutional collaborative publications) including UI (university-industry), UG (university-government), IG (industry-government), or UIG (Tijssen et al., 2009; Lei et al., 2012; Wang et al., 2014; Fan et al., 2015; Paswan et al., 2022). For instance, by calculating the number and percentage of the papers and patents in Northeast China, Zhu et al. (2022) found that the promoter of collaborative innovation system development is universities, academic research institutions and industries. The sectoral distribution of research output for India showed that UG collaborative publications increased, but G publications slight decreased after 2015 (Paswan et al., 2022). The research based on Chinese patent data shows that the core innovation strengths shifted from governments to universities, and then to industries during the whole process of scientific development. In addition, the relations between U and I have been intensified in recent years, while UIG collaborative publications remain weak (Lei et al., 2012). Fan et al. (2015) investigates the diversified resource of UI collaborative publications in Chinese research-oriented universities and found that the importance of collaboration with industries in the scientific contribution have been strengthened. These studies preliminarily demonstrate that institutional alliance with diverse attributes including heterogeneous resources and institutional frameworks, playing a crucial role in collaborative scientific knowledge production. However, the micro-level individual collaboration perspective exhibits theoretical limitations: excessive reliance on observable explicit knowledge outputs neglects critical dimensions including tacit knowledge flows during innovation processes, institutional coupling mechanisms, and synergistic effects generated by collaborative behaviors, thereby constraining comprehensive analysis of UIG collaborative innovation systems.

Triple Helix synergetic interactions

Another important perspective is to explore the interactions among them based on the Triple Helix model. Etzkowitz and Leydesdorff proposed that there are three distinguished dynamics including the economic dynamics of the market (industry), the internal dynamics of knowledge production (university), and governance of the interface at different levels (government) in innovation system. The three sectors—university, industry and government—interact with each other in promoting the development of knowledge economy (Etzkowitz & Leydesdorff, 1995). By applying Shannon-type information entropy, joint entropy, conditional entropy and mutual information generated in the interactions among the three sectors, the Triple Helix has been elaborated into a recursive model for explaining how the overlay of interactions operates on the institutional carriers (Leydesdorff, 2000, 2011), and thus brought a boom of quantitative studies of UIG interactive relationships (Etzkowitz & Leydesdorff, 2000; Leydesdorff, 2000; Leydesdorff & Sun, 2009; Park & Leydesdorff, 2010; Leydesdorff & Ivanova, 2014; Zhang et al., 2019). More uncertainties will be reduced in the whole system when the interactions among two or more sectors are reinforced. Distinguished from institutional diversity indicators, the entities in the system are no longer separate institutional spheres but intermingle with others to achieve self-organization. Triple Helix model describes the interactions of entities and its impact on the overall system.

Empirical evidence predominantly indicates that university-industry (UI), university-government (UG) and industry-government (IG) synergetic effects exhibit either stagnant or declining trajectories, whereas university-industry-government (UIG) triadic collaborations demonstrate an initial increase followed by persistent decline (Table 1). For instance, Kang et al. (2019) compared the institutional cooperation relationship based on the Triple Helix models in Beijing and Shanghai, finding that compared with the government and the industry, universities made major efforts for innovative research. Shanghai adopts UG bilateral interactions as its main form, while UI bilateral interactions in Beijing had become weaker gradually. The innovation system of UIG collaboration has formed in both cities, featuring reduced synergy shown by stronger bilateral collaboration than trilateral collaboration. Leydesdorff and Sun (2009) added the international collaboration dimension into traditional Triple Helix indicators and found that domestic bilateral and trilateral relations became gradually weaker, while the T-values of quadruple helix demonstrated a trend of first increasing and then decreasing. Leydesdorff, Ye and Xu have found that trilateral relations have generally shown a downward trend in varied countries including the US, the UK (Choi et al., 2015), Europe (Glänzel & Schlemmer, 2007), China (Ye et al., 2013), South Korea (Kwon et al., 2012; Yoon, 2015), Japan, Russia (Egorov et al., 2019), Bangladesh (Hossain et al., 2012), and Saudi Arabia (Shin et al., 2012).

Through systematic literature investigation, two critical limitations in prevailing research approaches can be found. First, assessing systemic synergy variation exclusively through fluctuations in the T-value (the indicator of synergy effect), while neglecting the critical role of institutional diversity in comprehensive evaluation may induce systematically skewed interpretations. For instance, elevated T-values coupled with low institutional diversity in a region signify scientific innovation monopolized by elite institutions, constraining knowledge diffusion and impeding sustainable development of the innovation ecosystem. Second, the interpretation of T-values is ambiguous. Some studies erroneously equate T-values with collaborative tightness measurements, while others inappropriately treat T-values as the exclusive indicator of overall systemic synergy effects, neglecting to

Table 1 The T-values of the different countries/cities among university, industry, and government relationships

Reference	Samples	Time span	Relationships	Results (T-values)					
				UI	UG	IG	UIG	UIG	UIG
Leydesdorff (2011)	South Korea	1973–2005	UIG	↓	↓	→	→	↻	
Hossain et al. (2012)	Bangladesh	1999–2010	UIG	↓	↓	↓	↓	↻	
Shin et al. (2012)	Saudi Arabia	1975–2010	UIG	-	-	-	-	↻	
Ye et al. (2013)	G7, Brazil, Russia, India, China, South Africa, South Korea, Netherlands, Indonesia	1971–2010	UIG	↓	↓	→	→	↓	
Xu et al. (2015)	USA, UK, Britain, China, Germany, France, Canada and Japan	2000–2014	UIG	-	-	-	-	↻	
Kang et al. (2019)	CI (Shanghai, Beijing),	2008–2017	UIG	↓	↑	→	→	↓	
Zhu et al. (2022)	Heilongjiang Province	2000–2019	UIG	↓	↓	↓	↓	↻	
Zhang et al. (2019)	Chinese Academy of Sciences (CAS)	1984–2016	UIC (C: CAS)	↑	↑	-	-	↑	
Leydesdorff and Sun (2009)	Japanese	1981–2004	UIGF (F: Foreign actors)	↓	↓	→	→	↓	
Kwon et al. (2012)	South Korea	1968–2009	UIGF (F: Foreign actors)	→	↻	→	→	↻	

The results of the qualitative research or the papers without annual changes in T-values have not been reported. “↑”, “↓”, “→” and “↻” indicate the upward trend, downward trend, stable trend and trend in inverted U-shaped curve, respectively. UIC indicates the relationships between/among the university, industry and the CAS

comprehensively consider indicators such as joint entropy and conditional entropy, inevitably leading to flawed analytical conclusions (e.g., Kang et al., 2019).

Research design

This study integrates micro-level institutional collaboration perspectives and macro-level systemic synergy interactions to establish a multi-tiered analytical framework, offering theoretical and methodological advantages for comprehensively deconstructing industry-academia-research collaborative dynamics. At the micro-analytical level, collaborative relationships will be measured through calculating the number/proportion of co-authorship publications on different types of collaboration pattern and institutional diversity. Institutional diversity, which can also be called as multi-sector participation, refers to the fact that academic research involves different types of sectors, such as enterprises, universities, governments, industries, and the third-party organizations. These sectors promote academic innovation through communication, knowledge sharing, and collaboration in the process of research and problem solving. This study introduces the interdisciplinary metric: Simpson's Index (D) to quantify the extent of heterogeneous knowledge resources contributed by diverse institutional entities toward shared research objectives. It was proposed by Edward Simpson in 1949 (Simpson, 1949), can be used to measure the diversity of species in a group, with larger values indicating lower species diversity. It can characterize two dimensions: variety, i.e., the number of species in a sample set (the more species there are in the sample set, the more "abundant" the group is), and balance, i.e., the relative abundance of different species. This indicator has been modified and applied in a wide range of fields. Typically, researchers in the field of bibliometrics use the Simpson's Index of Diversity (1-D) to measure the interdisciplinarity of papers, journals, institutions, disciplines, fields, etc. (Chen et al., 2015; Wang & Schneider, 2019). Larger values indicate greater diversity within a given data set. This indicator advances conventional studies of UIG collaboration by integrating balance assessment with institutional type richness quantification (variety), thereby mitigating innovation monopolization risks.

In addition, this study adopts a systemic perspective, employing the Triple Helix (TH) model to quantify information redundancy generated by UIG interactions within complex systems, thereby evaluating synergetic effects. It addresses micro-level deficiencies wherein the frequency of explicit collaborations is emphasized while implicit synergy effects remain overlooked. As mentioned above, many studies oversimplify T-values as relational intensity metrics while neglecting the evolutionary dynamics of systemic uncertainty. The misunderstanding may lead to analytical bias. Through mathematical modeling and simulation analysis, this research clarifies the algorithms, interpretation, and practical applicability of the Triple Helix Model. Furthermore, it extends its application to climate change field, uncovering the evolutionary mechanisms of university-industry-government synergy.

The specific research questions are as follows:

- (1) What is the institutional diversity of collaborative research in the field of climate change, at both a global level and national/topic-specific levels?
- (2) What are the Triple Helix interactions among universities, industries and governments in the field of climate change, at both a global level, and national/topic-specific levels?
- (3) What are the similarities and differences between institutional diversity and Triple Helix interactions among universities, industries and governments? How do their com-

plementary mechanisms synergistically combine within an integrated framework to systematically explain UIG collaborations.

To address the core problems, this study proposes a theoretical framework structured into three progressively hierarchical tiers (Fig. 1):

- (1) **Foundational Tier.** From a micro-institutional collaborative perspective, this tier examines explicit relationships shaped by formal collaborative mechanisms. To assess the diversity of institutional participation, this study introduces the Simpson’s Index of diversity, a widely used indicator of interdisciplinarity. It captures the extent to which different types of institutional actors contribute toward shared research objectives, thereby reflecting the level of cross-institutional resource integration. Universities typically contribute frontier theoretical knowledge, industries provide technological application expertise, and governments offer policy frameworks and real-world implementation scenarios. These heterogeneous knowledge sources form the basis for a robust and synergistic innovation ecosystem.
- (2) **Mechanistic Tier.** This tier adopts a macro-systemic synergistic perspective to examine implicit relationship shaped by institutions and environment. The value co-creation mechanisms demonstrate differential outcomes: optimal alignment generates innovation multiplier effects, whereas misalignment triggers efficiency erosion. Unlike analyses centered on individual collaborative behavior, the Triple Helix model assesses the systemic synergy of U–I–G interactions by measuring information redundancy within complex systems. Synergy determines value transformation, and optimal synergistic relationships can produce a “Multiplier Effect”. Although it has been adapted by many disciplines, the model is often conceptually misused. To address this problem, the study explicates the algorithm, interpretation, and practical applicability of the Triple Helix model through mathematical modeling and simulation analysis. It then extends the model’s application to climate change research to trace the evolution of U–I–G synergy mechanisms.
- (3) **Comparative Tier.** This tier employs temporal (2001–2021), topic-specific (topic mining based on NMF), and national dimensions (the top eight countries with the most publications) dimensions to reveal heterogeneous performance in both micro-level institutional collaboration and macro-level systemic synergies. The nonlinear dynamic

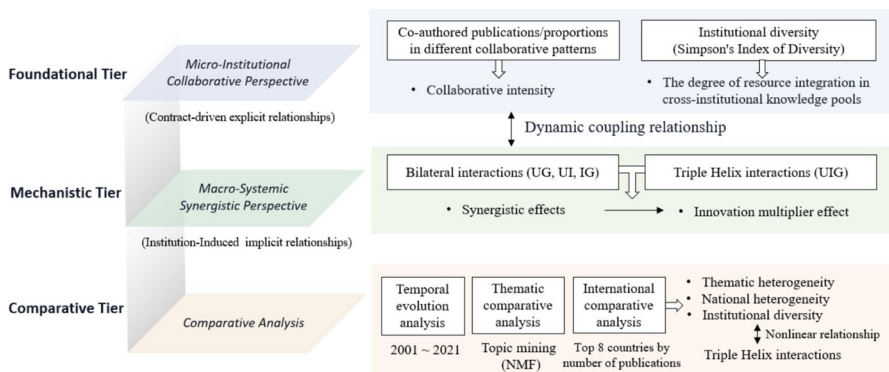


Fig. 1 Three-Tiered progressive theoretical framework

coupling relations between institutional diversity and systemic synergy is analyzed accordingly. Both institutional diversity indicator and Triple Helix model have been employed to clarify the relationships among universities, industries and governments of climate change research, considering not only the overarching perspective but also delving into country/territory-specific and topic-specific levels. The degree of sectoral participation, as measured by institutional diversity, was measured by institutional diversity indicator, reflects stability and inclusiveness of multi-actor collaboration in promoting scientific innovation.

The rest of this study is organized as follows: The data source, cleaning process and methodology were elaborated in Sect. “[Research methodology](#)”. The dynamic institutional diversity and Triple Helix interactions of universities, industries and governments were discussed in Sect. “[The dynamic diversity and Triple Helix interactions of universities, industries and governments](#)”. More detailed comparisons among topics and countries were explored in the Sect. “[The comparison research of Triple Helix interactions in different topics](#)” and Sect. “[The comparison research of Triple Helix relations in different countries](#)”. Finally, the conclusions, discussions and limitations were summarized in Sect. “[Conclusion and discussion](#)”.

Research methodology

Data collection and cleaning

As the gradually warming global climate system has been exerting a huge impact on the whole world, climate change has been extensively discussed among sectors like scholars, policy makers, environmentalists, and entrepreneurs. Issues of global warming, natural disasters, extreme weathers and human activities have made it more urgent for collaboration (Oreskes, 2004; Solomon et al., 2007; Shaw et al., 2010). Climate change is a typical interdisciplinary field featuring complexity, diversity, and comprehensiveness, which calls for integration of various sectors (Benton, 2013; McCright et al., 2013; Hellsten & Leydesdorff, 2016). The successful cases of UIG interactions indicate that knowledge transformation from academic to practice can reduce and alleviate the risk and negative impact of climate change to some extent (Etzkowitz, 2008; Nelson, 2013). For example, except traditional methods of tax preferences and research funding, Japanese government has made policies to support UI collaboration to minimize the negative impact from extreme weathers and natural disasters onto the social life. Japanese not only stimulated industrial technology changes in new energy by encouraging government procurement innovation, but also facilitated the formation of commercial modes capable of responding to new technology challenges in the market (Eppel, 1998; Mani, 2002; Sato, 2017). Improving the multiple-sector collaboration and exploring knowledge frontiers in more diversified collaboration are of advantages to deliver more innovative research, intervention measures, and technology and management methods. However, current research predominantly comprises qualitative case studies on UIG collaboration in the field of climate change, lacking empirical validation of quantitative relationships. For example, through interview survey, Lorenzo Compagnucci and Francesca Spigarelli analyzed qualitatively UIG collaboration in the region of Murcia, in the southeast of Spain, for alleviating chronic water shortage and improving agricultural

development in local areas (Compagnucci & Spigarelli, 2018). Lee and Mwebaza (2022) analyzed the UI interactions and proposed the Triple Helix strategy for facilitating climate technology transfer. López-Pérez et al. (2023) took the cases of the Smart Mobility and Smart Climate of PCT Cartuja (Science and technology park in Seville, Spain), attempting to resolve the conflicts of public–private partnerships. In order to fill this gap, this study collects publications from this field as samples to examine UIG interactive relations.

With reference to previous bibliometric studies about climate change (Haunschild et al., 2016; Zyoud & Fuchs-Hanusch, 2020; Fu & Waltman, 2022; Song et al., 2023), the keywords including “climate chang*”, “climate variabilit*”, “global warming”, and “climate warming” present in the title or abstract were retrieved with document type as articles in the contemporary research from the Science Citation Index Expanded and Social Sciences Citation Index in Web of Science Core Collection, and the time span is from 2001 to 2021. As a result, a total of 194,954 articles were collected.

The identification of institutional attributes was extracted and classified specifically. The ITGInsight software was used to extract institution and country/region information from the author’s address field (Wang et al., 2021). However, because of the different writing styles and coding rules (Richardson, 2010), the ambiguity of institution names seems to be unavoidable. The textual similarity calculation function embedded in the software will be used to disambiguate institution names, supplemented by manual review. In the process of manual supplementation, we repeated experiments to supplement the unrecognized organizations, and constantly adjusted the organization writing format to reduce the discrimination, etc. After several rounds of manual review and correction of institutions, the institutions with a frequency of occurrence more than 30 were obtained, and 270 terms were used to identify the institutions of U, I and G. A total of 50,403 sectors and their corresponding attributes are eventually identified (1 if the institution appears in the author’s address field, 0 otherwise). The ratio of identified attributed institutions to the total number of institutions for each publication was used to calculate the institution identification rate of the publication. The total samples had an average institution identification rate of 96.07%, with unrecognized institutions being excluded from the dataset (Table 2).

Based on the classified institution, publications are classified into 7 types of collaborative patterns, including papers published by a single institution (U, I, or G), bilateral institutional collaboration of UI, UG, or IG, and trilateral institutional collaboration of UIG.

Table 2 Classification rules of different category of institutions

Categories	Author’s address field
University (U)	Univ, UNIV, Coll, Acad, UCL, Inst Technol, etc. (115 terms in total)
Industry (I)	Corp, LLC, GmbH, AG, Inc, Ltd, Soc, LTD, Fdn, Trust, Sinopec, Nature Conservancy, etc. (43 terms in total)
Government (G)	Natl, Govt, Minist, Hosp, CNRS, USDA, Bundes, NIH, Fed, NASA, etc. (112 terms in total)

Indicators

Diversity

Two indicators with a progressive relation, diversity and Triple Helix indicator, have been used to analyze the UIG relationships in the field of climate change. The former is a composite indicator that includes the number and proportion of collaborative publications from cross-institutional collaborations and the Simpson’s Index of Diversity. The number and proportion of UIG collaborative outputs has been early employed to provide the unique sources of information for exploring the magnitude and intensity of UIG collaborative relations (Tijssen et al., 2009). In recent years, the Simpson’s Index of Diversity has been applied to measure the institutional diversity in disciplines of education and management science (McLaughlin et al., 2016), reflecting the contributions of different sectors to a common goal. The value of this indicator ranges from 0 for single institution articles to 0.67 for article contributed by UIG collaboration with the same number of different types of sectors ($U=I=G=1$). It can be formulated as follows (Simpson, 1949):

$$1 - D = 1 - \sum_{i=1}^S p_i^2 \tag{1}$$

where, S represents the number of institutional types, and p_i means the ratio of the number of publications of institution i to the number of publications of all institutions. The joint probability of randomly selecting two entities is p_i^2 .

Triple Helix indicator

The relationship among the three sectors was measured by the Triple Helix indicator, which was relevant to entropy. Shannon has defined the information entropy $H_i = - \sum_i p_i * \log_2 p_i$ as the occurrence probability of random events, and the unit is bit. The bigger the uncertainty of events, the bigger the entropy value is. In the case of two variables (i and j), H_{ij} can be calculated as:

$$H_{ij} = - \sum_i \sum_j p_{ij} * \log_2 p_{ij} \tag{2}$$

Among them, p_{ij} is the joint probability distribution of i and j , and H_{ij} is called the joint entropy. The total uncertainty in i and j (H_{ij}) can also be expressed as the sum of two-dimensional uncertainties minus the mutual information (or transmission) T_{ij} (Leydesdorff & Ivanova, 2014):

$$H_{ij} = H_i + H_j - T_{ij} \tag{3}$$

It can be seen from formula (3), when two variables interact, the total uncertainty will increase as the uncertainty ($H_i + H_j$) of each variable increases, but decrease as the mutual information (T_{ij}) increases in the meantime.

When three variables (i, j and k) interact, the calculation formula for the interaction uncertainty is as follows:

$$T_{ijk} = H_i + H_j + H_k - H_{ij} - H_{ik} - H_{jk} + H_{ijk} \tag{4}$$

The negative value of T_{ijk} indicates a reduction of the uncertainty. The larger the absolute T-values, the stronger the interactions between/among different variables. The previous research on the interpretation of the Triple Helix tends to draw conclusions about the synergistic effect of the whole system based only on T-values. For example, Kang et al. (2019) considered the T-value as a measure of the tightness of universities, industries and governments. In fact, although more negative T-values are beneficial in reducing the uncertainty of the system, it is lacking in rigor to determine whether the total uncertainty of the system has increased or decreased only according to the change in T-values. This is because H_{ijk} (Formula 5) is influenced by the uncertainty of the single variables (H_i, H_j and H_k), the uncertainty of the two variables (H_{ij}, H_{ik} and H_{jk}), and the triple interaction information (T_{ijk}). When the growth rate of H_i, H_j and H_k are much faster than that of the negative values of T_{ijk} , the overall uncertainty of the system is still raised.

$$H_{ijk} = (H_{ij} + H_{ik} + H_{jk}) - (H_i + H_j + H_k) + T_{ijk} \tag{5}$$

The extant studies have adopted the Triple Helix indicator to measure the amount of mutual information among different sectors (Park & Leydesdorff, 2010; Leydesdorff & Ivanova, 2014; Leydesdorff & Zhou, 2014; Yoon & Park, 2017). Considering the consistency of the theory and internal mechanisms, the above formulas was applied to analyze the dynamic interactions among UIG. Hence, the formulas can be rewritten as:

$$T_{UIG} = H_U + H_I + H_G - H_{UI} - H_{UG} - H_{IG} + H_{UIG} \tag{6}$$

$$H_{UIG} = (H_{UI} + H_{UG} + H_{IG}) - (H_U + H_I + H_G) + T_{UIG} \tag{7}$$

In this study, UIG bilateral and trilateral interactions in the field of climate change were explored through Triple Helix indicator, as well as the comparison of Triple Helix relationships among different topics and countries.

In reverse to the linear model, the relationship between UIG collaborative patterns and T-value of a system in the Triple Helix model is abstract and complex, which is presented visually in the form of a schematic diagram by using Matlab software (Fig. 2). The X, Y, Z axes in Fig. 1 are the frequency of occurrence of the three different UIG collaborative patterns. The absolute T-value with the system is the largest when the frequency of occurrence of different collaboration patterns is equal, while the T-value is minimized when a certain pattern of

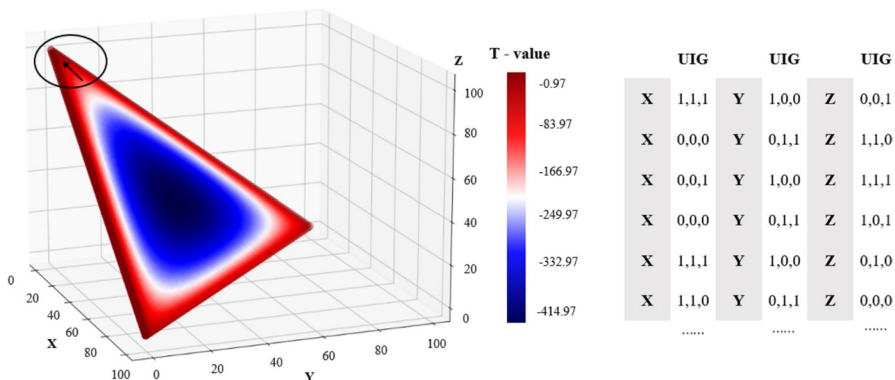


Fig. 2 The relationship between UIG collaboration patterns and T-values within a system

collaboration is entirely dominant in the dataset. For example (right side of Fig. 1, line 1), the X-axis represents UIG collaborative publications ($U=I=G=1$), the Y-axis is the publications contributed only by universities ($U=1, I=G=0$), and the Z-axis means the publications from governments ($G=1, I=U=0$). The highest synergy of UIG interactions occur when the three patterns of collaboration occur with equal frequency, with the T-value of -414.97 (dark blue). When the publications from governments increases (higher values on the Z-axis) and the publications from the other two patterns of collaboration decreases (lower values on the X-axis and Y-axis), the T-value migrates to the red zone, thereby the synergy is weakened.

All possible patterns of collaboration (right side of Fig. 1) in the field of climate change have been traversed and presented in three-dimensional diagrams. The similar relationship between UIG collaboration patterns and T-values has been found. Figure 1 is presented as a case.

Topic mining

In order to explore the disparities of the Triple Helix interactions among three organizations in different topics in this field, the sub-topic of climate change will be further explored. NMF excels in handling high-dimensional sparse datasets due to its inherent sparsity-inducing properties, which automatically filter out noise and prioritize dominant patterns. This makes it particularly suitable for short-text topic mining tasks such as bibliographic data analysis. Empirical results demonstrate its superior performance in topic coherence metrics compared to probabilistic methods like Latent Dirichlet Allocation (LDA). Neural network-based models (e.g. BERTopic) demonstrate limitations in short document scenarios due to their dependence on comprehensive textual statistics, often resulting in unreliable topic distribution estimations. Therefore, NMF is the best model for topic mining analysis in this study, which is a dimensionality reduction technique grounded in linear algebra, which decomposes a non-negative input matrix $V \in R^{m \times n}$ into two lower-rank non-negative matrices $W \in R^{m \times k}$, (representing feature-topic relationships) and $H \in R^{k \times n}$, (representing topic-sample distributions), such that $V \approx WH$. The optimization objective is achieved by minimizing reconstruction errors, typically measured by Frobenius norm ($\|V - WH\|_F^2$), under explicit non-negativity constraints. This topic model simultaneously generates the topics of words and documents, mining the potential semantic relations rather than the literal meaning, providing better clustering and interpretation of topics (Kuang et al., 2015). Since its inception, NMF has been widely used in the fields of computer vision, chemometrics, bioinformatics and scientific topic evolution (Wang et al., 2012; Qian et al., 2020; Berahmand et al., 2022; Hamamoto et al., 2022). In this study, NMF was used for topic clustering based on the title and abstract of publications in the field of climate change. The Triple Helix time-series analysis based on different topic data can verify the consistency of the trend of topics and the overall field synergies on the one hand, and analyze the differences in the Triple Helix relationships among the topics in-depth on the other hand.

Results

The dynamic diversity and Triple Helix interactions of universities, industries and governments

Trends of institutional diversity of UIG collaboration

The number of publications from different institutions are shown in Fig. 3a and b. In terms of single-institutional publications, universities are the primary institutions of academic research in the field of climate change, exhibiting an exponential growth trend from 950 in 2001 to 19,671 in 2021. The number of publications contributed by industries is less than that of the universities, with a slow linear growth trend. After climbing still 2011, the number of publications from governments became stable until 2019, and then increased from 404 in 2019 to 581 in 2021 which might be partly attributed to the emphasis of governments on climate change in recent years.

From the perspective of cross-institutional collaboration, we have witnessed a large number of UI collaborative publications and UG collaborative publications in recent decades. In particular, UI collaborative publications increased dramatically from 2019 to 2021, which may be due to the fact that enterprises are increasingly emphasizing the economic value of the technology transformation of academic research. However, IG collaborative publications have always maintained at a relatively low level in terms of quantity, which may suggest that the appropriate and sustainable mechanism of research collaboration based on the common

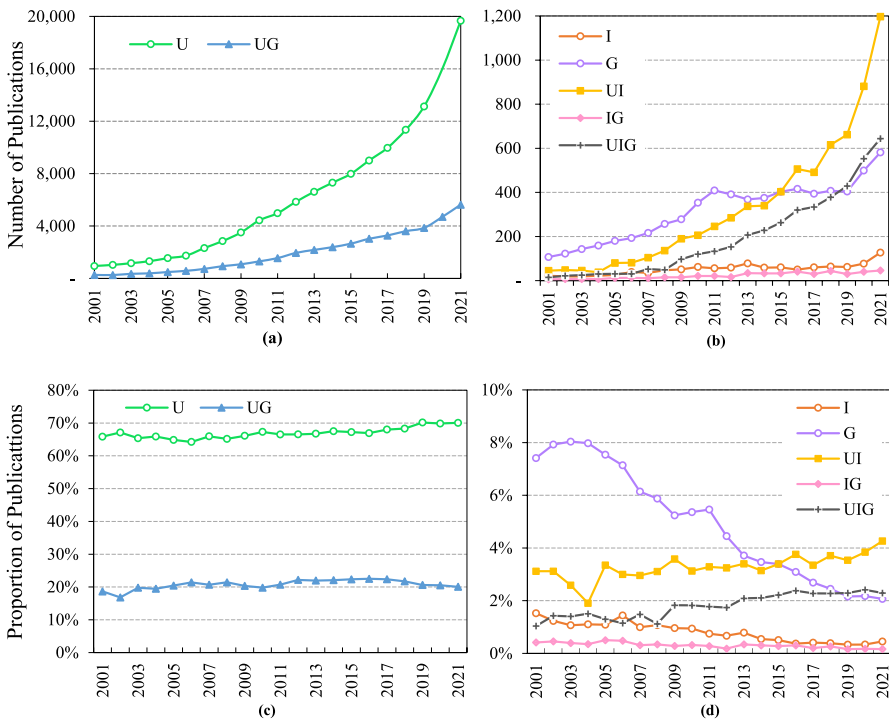


Fig. 3 Trends of publications published by various institutions (2001–2021)

interests has not yet been developed. The number of papers published by UIG increased from 1443 in 2001 to 28,080 in 2021, reflecting the enhancing UIG interactions.

There has been a gradual increase in institutional diversity in climate change research from 0.106 in 2001 to 0.121 in 2016 (Fig. 3), which is manifested as the increase in the proportion of cross-institutional (UG, UI and UIG) collaborative publications and decreased proportion of single-institutional (G and I) publications. Specifically, although the proportion of U publications remained at a high level over the past 20 years, diverse patterns of collaboration were increasing at the same time, like UG, UI and UIG collaborations. In addition, the results presented in Fig. 1b and d reveal that although the number of publications published by G has increased rapidly from 107 in 2001 to 581 in 2021, the proportion of publications has declined significantly (from 7.4 to 2.3%). The similar phenomenon also occurs in industries. By contrast, G and I are increasingly inclined to collaborate with U, thereby reflecting the increase in the proportion of UIG, UG and UI collaborative publications.

The period 2016–2021 exhibits a downward trend in institutional diversity (Fig. 4). Although there are increasingly more institutions conducting academic research (with the most significant growth in the number of U) (Tijssen et al., 2009), the increase in the proportion of U publications is higher than the decline of the G publications, and at the same time, the decline in the proportion of UG collaborative publications is higher than the increase in UI collaborative publications.

The evolution of the Triple Helix interactions among UIG

The dynamic evolution of the bilateral collaboration (UI, UG, and IG) and Triple Helix interactions of UIG through mutual information on the basis of information entropy theory and Triple Helix indicator has been displayed in Fig. 5. The unit of information entropy can be expressed by millibits (mbits). The mutual information of UG interactions fluctuated between 70.00 and 89.37 mbits within 2001–2005, followed by a sharp reduction from 88.93 to 19.99 mbits in 2021. The uncertainty of the whole system (H_{UG}) was decreased, not as a result of university-government interactions, but

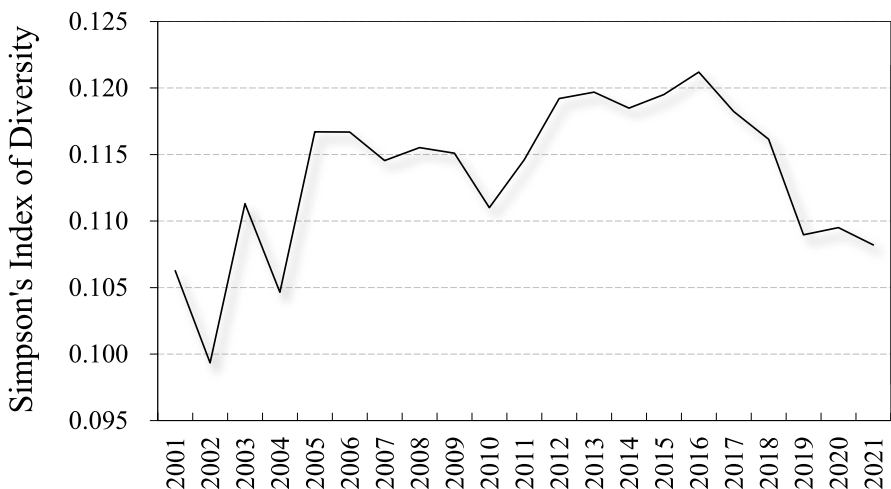


Fig. 4 The institutional diversity of UIG collaboration

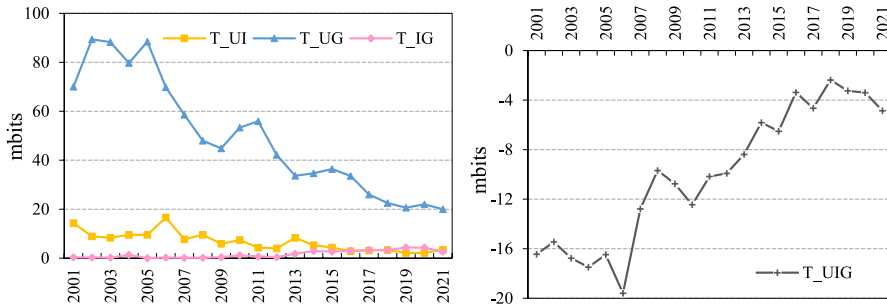


Fig. 5 The mutual information in two/three dimensions in the field of climate change. *Note:* T_{UI} , T_{UG} and T_{IG} represent the two-dimensional mutual information of UI, UG, and IG, respectively. The Triple Helix interactions can be characterized by T_{UIG}

rather the reduced uncertainty of the university (H_U) (Appendix Table S2). Similarly, although the weakening T_{UI} values have little effect reducing on the uncertainty of the UI sub-system, the H_{UI} values were still declining because of the slump of H_U . The T_{IG} values have remained stable growth after 2012, which reveals the stabilization of IG interactions.

The negative values of T_{UIG} from 2001 to 2021 indicate that the UIG collaboration system of climate change was basically formed. The dynamics of the UIG interactions in terms of the longitudinal trend varied considerably. The right side of Fig. 5 indicates a strong UIG integrated system in 2006 (19.60 mbits) after a period of negative growth of T_{UIG} values, but it plunged sharply from 2006 to 2018, which perhaps resulted from some complex external environmental factors, such as international collaboration or research funding (Leydesdorff & Sun, 2009; Kwon et al., 2012; Ye et al., 2013). In fact, the uncertainty of the whole system has shown a downward trend in the past two decades (H_{UIG}), even though the Triple Helix relationship has been represented a long-term weakening. The uncertainty of UIG system has been highly eroded by the reduction of H_U (Table S2 in appendix). T_{IG} -values have remained at a low level, even if a slight rise since 2013.

The relationship between institutional diversity and synergy demonstrates dynamic coupling characteristics: Elevated institutional diversity signifies sufficient cross-institutional resource integration with corresponding synergy enhancement, while excessive diversity may concurrently elevate collaboration costs and risks. The T-value quantifies system self-organization capacity, where information redundancy beyond critical thresholds may induce innovation emergence. These dual dimensions constitute essential components in evaluating scientific collaboration frameworks: diversity ensures collaborative breadth through combinatorial possibilities, while synergy determines innovative depth via knowledge recombination efficiency.

The comparison research of Triple Helix interactions in different topics

Institutional diversity UIG collaboration in different research topics

Based on the NMF text mining algorithm, the publications in field of climate change mainly focus on eight topics, including climate simulation model, climate technology, biodiversity, agriculture, physical science basis, paleoclimatology, climate policy, and vegetation (Appendix, Table S1). Research topics have been determined by referring to the

report of the Intergovernmental Panel on Climate Change, i.e., “Climate Change 2021: The Physical Science Basis” (Masson-Delmotte et al., 2021) and the relevant research (Fu & Waltman, 2022).

Contributing the largest number of papers, with a share of 20.04%, paleoclimatology topic mainly focuses on explaining historic changes of the climate system from the time perspective by long term records from “lakes”, “precipitation”, “sediments” and other sources covering the entire history of the earth (“Holocene”). The second place in terms of the number of publications is taken by climate policy, with a share of 19.37%. Research on climate technology (15.47%) mainly attempts to alleviate the challenge of climate change through innovative technologies, with such frequently occurring words as “energy”, “emission”, “carbon dioxide”, “production” mostly related with climate technological goals. Research on climate simulation models (12.03%) and physical science basis (10.43%) attempts to describe, simulate, forecast and analyze the natural and social impacts of climate change. The former focuses on simulating the phenomena and impacts of climate change, paying more attention to fine-grained climate change issues compared with research on physical science basis. Physical science basis analyzes the issue of global warming and its impact from the angle of physical sciences, representing a macro-summary of climate sciences. Biodiversity research (11.32%) mainly illustrates the impact of climate change on ecology, species and the environment. Research on agriculture (5.79%) and vegetation (5.54%) delivering a small number of publications, mainly discuss the impact from climate change on the ecological environment (Fig. 6).

Institutional diversity measured by Simpson’s Index of Diversity in different topics shows the inconsistent results with the total number of publications, which is related to the proportion of cross-institutional collaborative publications (Fig. 7). Typically, topics of vegetation, biodiversity, and climate simulation model do not outperformer in terms of the number of publications than the topic of paleoclimatology, climate policy and climate technology, but show stronger institutional diversities. This performance could be mainly attributed to the relatively high proportion of cross-institutional collaborative papers and a comparatively low proportion of papers from single institutions.

More specifically, the proposition of UG publications in vegetation (3135 publications, 29.2%) and climate simulation model (6269 publications, 26.9%) are higher than the other topics. Biodiversity has attracted more tripartite attention of universities, governments, and industries simultaneously, with the highest proportion of UIG publications (788 publications, 3.6%) and the increasing institutional diversities from 0.11 to 0.16 (Appendix Fig. S1).

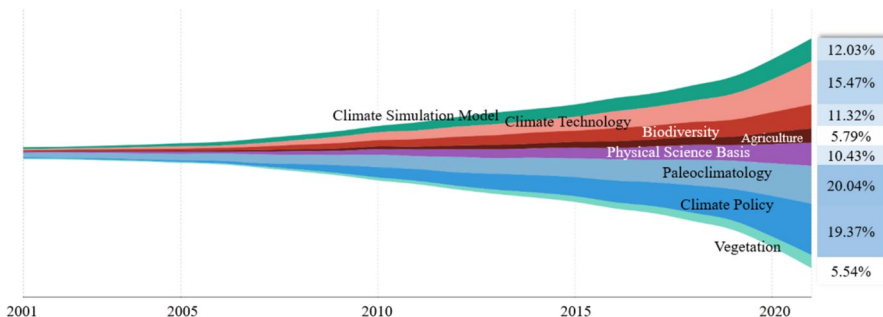


Fig. 6 Trends in the number of publications in the eight topics (2001–2021)

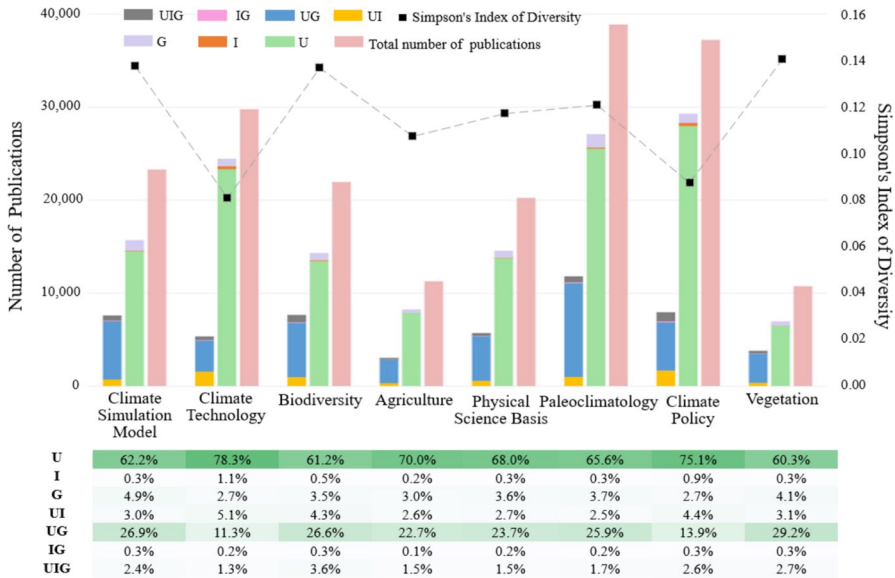


Fig. 7 The different attentions of UIG to eight topics in the field of climate change

In contrast, paleoclimatology topic with the highest total number of publications maintains at a medium level of institutional diversity (0.12). Climate technology is correlated with energy and emissions, attracting high attention from universities (23,292 publications, 78.3%) but weak participation of government, which leads to relatively low publications of UG (3351 publications, 11.3%) and UIG (378 publications, 1.3%). Note that it has attracted more industrial participation than other topics, thereby generated more publications from I (328 publications, 1.1%) and UI (1531 publications, 5.1%). Climate policy has attracted more participation of universities (27,943 publications, 75.1%) and industries (343 publications, 0.9%).

Triple Helix interactions in different topics

Figure 8 shows the significant disparities of T-values in different topics. The T_{UG} -value on the topic of climate simulation model is highest (47.56 mbits), but represents weak relationship between U and I (0.93 mbits). On the contrary, the topics of climate policy and climate technology topic shows weak interactions of UG, while mutual information of UI of UIG is the most two highest, indicating that the strong willingness of enterprises for absorbing innovative technologies and the transformation of research achievements from universities. The degree of mutual information in UI interactions in agriculture lies at a low level in eight topics, but with medium value of T_{UG} . Topic of paleoclimatology is committed to exploring the reasons, processes, distribution and evolution in the formation of the climate during the geologic period, with the aims of predicting future trends in climate change, solving resource and environmental problems, as well as providing information for policy-making. Due to the complexity of the theories and the challenge of translating academic achievements into economic values, industries with poor research capability are reluctant to participate in the collaborations with universities or governments, the

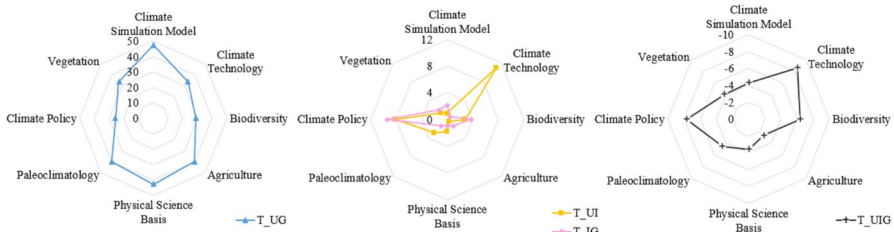


Fig. 8 Mutual information in bilateral/trilateral relations of UIG in eight topics. *Note:* T_{UI} , T_{UG} and T_{IG} represent the two-dimensional mutual information of UI, UG, and IG, respectively. The Triple Helix interactions can be characterized by T_{UIG}

T_{IG} and T_{UI} values of paleoclimatology are at a relatively low level (1.32 and 2.82 mbits, respectively).

The analysis of the UIG collaboration network and the trends of T-values in the eight topics are presented in Fig. 9 where the green, orange and purple nodes represent universities, industries and governments, respectively. The nodes are labeled with the proportion of independent publications, while the edges are marked with the proportion of collaborative publications. The line graphs indicated the longitudinal trends of T-values for eight topics.

The trends of T-values are similar across these eight topics (Fig. 9). Typically, the T_{UG} values in most topics fluctuated within 50–180 mbits in the early stage, but gradually weakened in the middle and later stages. The uncertainty of the UG collaborative subsystem has been synchronously decreased, which is mainly due to a significant reduction of H_U , suggesting that universities have been assuming an increasingly predominant role in research collaborations.

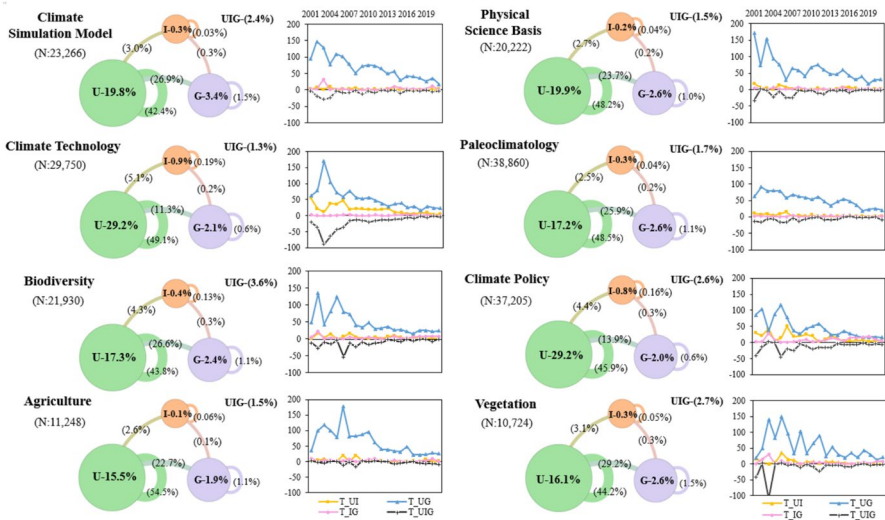


Fig. 9 The Triple Helix collaboration networks and the longitudinal trends of T-values in eight topics. *Note:* N denotes the total number of publications and the percentages on links and nodes indicate the proportion of this type of publication pattern

T_{IG} values in the eight topics have been maintained at a low level within 21 years, which indicates that an adequate collaboration sub-system of IG has not yet matured. The similar phenomenon occurs in T_{UI} values. With a slight difference, the topic of climate technology has a higher percentage of publications from universities or industries at 29.2 and 0.9%, respectively, as well as a higher percentage of UI collaborative publications than the other topics (5.1%). Environmental governance policies in various countries encourages industries to collaborate with universities on clean energy, climate-smart agriculture, sustainable transportation, net-zero emission technologies, carbon capture, utilization and storage, thus facilitates good UI interactions.

Gradually weakening UIG interactions appear in most topics, representing the reduction of T_{UIG} values, especially in climate technology and vegetation. T_{UIG} values in agriculture, paleoclimatology, climate simulation model and physical science basis consistently fluctuated slightly at low levels. In addition, biodiversity has the highest percentage of UIG publications (3.6%) in the eight topics, whereas the interactions of them was insignificant. This performance suggests that the tighter relationship of UIG does not imply the higher T-value, and the collaboration and interactions of entities in a system shows distinctive characteristics of relationship among these entities.

Certain topics may defy conventional positive correlations between institutional diversity and synergy. As evidenced in the topic of Climate Technology, constrained diversity (Simpson Index = 0.08) coexists with superior synergy effect (T-value = -90.21), demonstrating that focused institutional clusters can achieve higher knowledge recombination efficiency than broad-but-shallow collaborations through policy-enhanced interaction density.

The comparison research of Triple Helix relations in different countries

Institutional diversity UIG collaboration in different countries

Many countries have been exploring the diverse patterns of collaboration among the government, the industry and universities in the field of climate change. This study investigated and compared the institutional diversity in the top eight countries with a large number of publications.

Universities and governments have taken on more active roles in academic achievements in the field of climate change than industries. The country with the highest percentage of U publications is China (74.22%), followed by Germany, the USA and the UK (Fig. 10). In Canada, France, and Spain, G publications are much more than I publications, with a difference of more than 15 times, while the gap in the UK and Germany is relatively small, within four times. In terms of cross-institutional publications, UG collaboration are more frequent than other patterns of collaboration, followed by UI and IG collaboration. The France has the highest percentage of UIG collaborative publications (6.34%), while the proportion of UIG collaborative publications in China is the lowest (1.42%) among the top eight countries.

The institutional diversity of climate change research in France was lower than the USA, Canada and Spain at 2001, but then rose rapidly from 0.12 in 2002 to 0.26 in 2014 and has gradually achieved the highest institutional diversity since 2009 (Appendix Fig. S2). Spain ranks second in terms of institutional diversity (0.17), which might relate to its high proportion of collaborative publications (41.90%). China contributed the second highest number of papers in the world, but it has the lowest level of institutional diversity (0.10), which

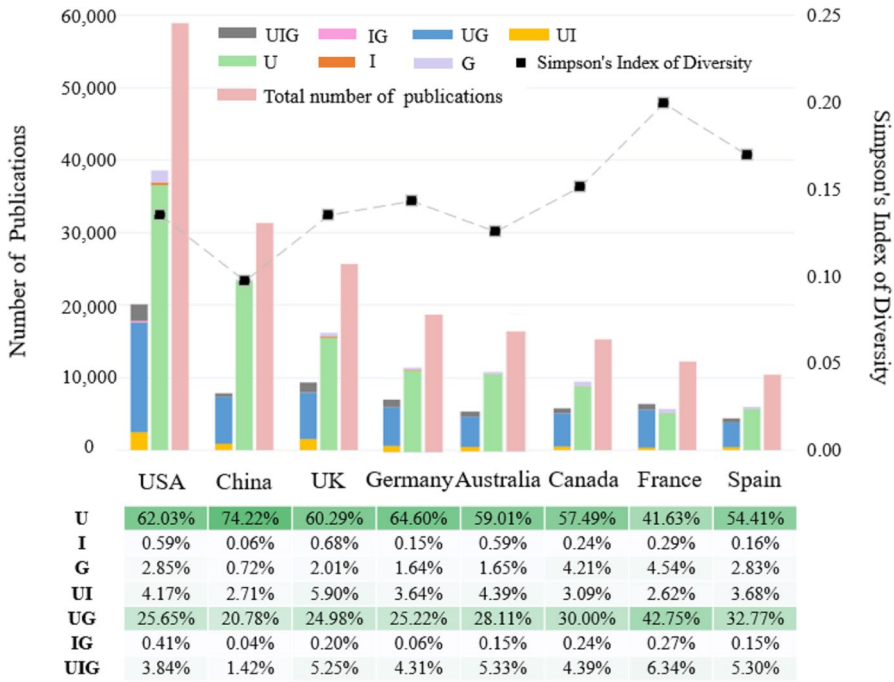


Fig. 10 The number of publications published by the top eight countries

may because of the highest percentage of single-institution publications (75.05%) and the lowest percentage of cross-institutional collaborative papers (24.95%). The USA, the UK, Germany, Australia, and Canada have the moderate level of institutional diversity (within 0.13–0.15) and stable development trends (Appendix Fig. S2).

Triple Helix interactions in different countries

The T-values of the eight countries during 2001–2021 has been shown in Fig. 11. China showed stable T-values at a weak level, possibly because of the highest percentage of domestic collaborative publications in universities (64.0%) and the lowest percentage of cross-institutional publications. To enhance the interactions of the integrated system, it can be suggested that China could encourage cross-institutional collaboration and introduce appropriate policies, regulations and incentive mechanisms for shaping and even enhancing the UIG interactions. The bilateral collaborative relations in Germany also maintained a stable trend, while the trilateral interaction is slightly unstable in 2001–2007.

The other six countries experienced a decreasing trend of T-values overall. Specifically, although T_{UG} values and T_{UIG} values in the USA have moved toward a negative direction in the past two decades, the interactions in recent years are still better than the UK, China, Germany, France. T_{UI} values of the USA remained at a high level from 2001 to 2010, which explains that the strong bilateral interactions between universities and industries have benefit to the frontier knowledge transfer from universities to industries. Hence, increasing R&D investments, sharing open and collaborative data and setting up user-driven innovation projects or even research centers with universities are conducive to enhancing the

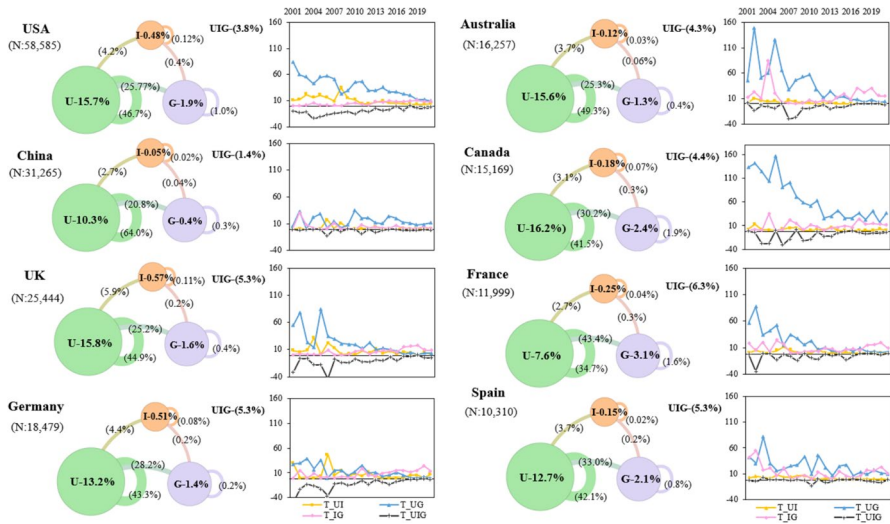


Fig. 11 The Triple Helix collaboration network and the longitudinal trends of T-values in eight countries. *Note:* N denotes the total number of publications and the percentages on links and nodes indicate the proportion of this type of publication pattern

knowledge innovation strength and absorptive capability of industries (Zhang et al., 2016; Taratori et al., 2021). The UK has a higher share of UI collaborative publications (5.9%) than other countries, while T_{UI} values are lower than that of the USA with a lower proportion of UI collaborative publications (4.2%). Early in the twenty-first century, the T_{UI} values in Canada and Australia outperformed than other countries, but declined rapidly in recent years, which is mainly because of the rapid decline of H_U .

The relationship between organizational diversity and systemic synergy demonstrates nonlinear dynamic associations. Empirical studies reveal distinct patterns: The Triple Helix innovation systems in the UK, Canada, USA, Australia, France and Germany exhibit high diversity coupled with strong synergy effects, whereas Chinese research demonstrate constrained diversity with correspondingly lower synergy effects.

Conclusion and discussion

This study investigates explicit cross-institutional collaborative relationships and implicit systemic synergistic interactions from both micro and macro perspectives. The former reflects the degree of cross-institutional resource integration, which contributes to the development of a diversified knowledge ecosystem that facilitates UIG interactions and innovations. The latter manifests the innovation knowledge multiplier effects emerging from institutional interactions within self-organizing systems. This theoretical framework not only complements the Triple Helix model but also enhances comprehensive understanding of scientific research collaboration mechanisms, demonstrating strong general applicability across a wide range of research fields. A comprehensive understanding of the dynamic and evolving landscape of the university-industry-government relationships in the field of climate change were explained based on this theoretical framework. This approach encompasses exploring the richness of institutional

collaboration in academic research via institutional diversity and, concurrently, employing analytical tools such as T-values, and joint entropy to meticulously analyze the intricate interactions among universities, industries, and governments in a system. The increase in the proportion of single-institutional publications and the decrease in the proportion of cross-institutional collaborative publications could influence the probability of occurrence of different collaboration patterns, which in turn reduces the uncertainty (T-value) of a system.

The institutional diversity of academic research in the field of climate change showed an overall tendency of increasing during 2001–2015 and then decreasing during 2016–2021. This phenomenon implies that the willingness of different sectors to participate in academic research has been enhancing for a long time and the system of academic collaboration with pluralistic participation has been gradually maturing. More specifically, in terms of single-institutional publications, the universities have always been the most vital knowledge innovation sectors (72.05%) (Kang et al., 2019), while the enthusiasm of the government for independent research have gradually declined. Industries are more likely to focus on the application and protection of innovative outputs, resulting in insufficient attention on traditional academic research (0.56% single-institutional publications). In terms of different topics, industries are more focused on Climate Technology research, while universities pay more attention to the basic academic research with strong theoretical foundation like paleoclimatology, climate simulation model and biodiversity. The topics of climate policy and climate technology have attracted joint attention from UIG. Multi-institutional collaboration can establish reasonable common goals on the basis of understanding the needs of all parties, contributing to the accumulation of funds and the transformation of academic achievements, as well as enhancing the stability and sustainability of knowledge innovation. UI, UG and UIG collaborative publications have become increasingly frequent, but IG collaborative publications maintained at a low level (Shin et al., 2012; Ankrah & Omar, 2015).

Triple Helix indicator has been used to measure the degree of disorder of different collaboration patterns in the system. The absolute T-value is maximized when all possible collaboration patterns occur with equal probability. In fact, due to the increasing dominance of universities, the T-values of bilateral and trilateral integrated system in the field climate change have been gradually declining even though there were small fluctuations in the early stage (Leydesdorff & Sun, 2009; Ye et al., 2013; Xu et al., 2015), except for IG interactions. For instance, in terms of different countries, the bilateral interaction of UG is the dominant form of interactions in system, but UI, IG and UIG interactions are inactive even though many countries have released a series of policies to promote the relationships among them. The profound reasons are the different behavioral logic, objective and culture among three sectors (Bruneel et al., 2010; Efi, 2014; Kafouros et al., 2015). This phenomenon indicates that when a pattern of collaboration occurs frequently, the possibility of uniform occurrence of other possible patterns of collaborations will be weakened, thereby reducing the uncertainty of the whole system. Hence, it may be imprudent to draw conclusions of system synergies only based on T-values while ignoring the impact of subsystem uncertainty on the overall system.

According to the analyses of the institutional diversity and the Triple Helix model, it can be seen that measuring the effectiveness of institutional collaboration through a single method is arbitrary. They are complemented each other to present a comprehensive performance. The diversified institutional collaborative pattern is conducive to the improvement of the T-values, while T-values are lower in systems where a single collaborative pattern occupies a monopoly position. For instance, the USA has the highest number of collaborative publications, with a high level of the Triple Helix interactions in a long period of

time, which is resulted from the encouragements and incentive policies about conducting in-depth and broaden collaboration among different institutions. Conversely, the Triple Helix interaction in China is far weaker than the other countries, which may be related to the excessively high proportion of publications issued by universities. Hence, countries could adopt different University-Industry-Government (UIG) collaborative strategies based on their systemic characteristics. The United States exhibits persistent advantages in UI collaboration efficiency, evidenced by sustained high T_{UI} -values. However, the risks in UIG synergy degradation necessitate some interventions. Firstly, existing strengths should be leveraged through scaling proven collaborative pattern like NSF's Industry-University Cooperative Research Centers (IUCRCs), requiring federal grants to involve at least two institutional stakeholders (Adams et al., 2001). Secondly, a Triple Helix optimization framework could be established through mission-oriented alliances, where governments strategically coordinate UIG collaborations in complex problem domains (Seppo et al., 2014; Meissner et al., 2018).

In China, the predominant issue lies in the institutional rigidity of university-dominated collaboration patterns, coupled with low heterogeneity knowledge integration capacity. To address this question, Chinese governments successively launched the “Joint Development Project of IUR”, “Law of the People’s Republic of China on Scientific and Technological Progress” and “Law of the People’s Republic of China on Promoting the Transformation of Scientific and Technological Achievements” to promote the interactions among three sectors (Sun & Cao, 2015). The previous research indicates that decision-making behaviors of primary stakeholders are significantly influenced by factors such as incentive-penalty mechanisms, cost-sharing arrangements, and benefit distribution frameworks (Li et al., 2019). Consequently, governments could strategically formulate reward-discipline systems while concurrently establishing equitable benefit distribution mechanisms within UIG collaborations. Such strategic alignment aims to facilitate the convergence of objectives among governments, industries, and universities through institutionalized coordination (Ma et al., 2024).

In Canada and Australia, UIG/UG synergy effects have declined significantly. This can be addressed by deepening the “HU Revitalization Plan,” linking university technology transfer budgets to UI collaboration revenue growth rates, and requiring major scientific infrastructure projects to establish UIG tripartite governance committees (Dollinger et al., 2018). For the countries like France and Spain demonstrating high institutional diversity yet suboptimal synergy effects, structural reforms to competitiveness cluster programs are warranted. For instance, reducing weightage on quantitative UIG entity counts, as well as creating flexible collaboration mechanisms to activate potential synergy effects.

There are some limitations of this study. Given the normative and availability of a large-scale dataset, we measured the Triple Helix interactions among UIG through the co-author papers. In fact, it can also be reflected in other formal and informal behaviors, such as individual consultancy, information exchange forums, conference, joint lectures, students’ involvement in industrial projects, joint supervision of PhDs and Masters and jointly-founded innovation centers (Shenhar, 1993; Barringer & Harrison, 2000; Santoro & Gopalakrishnan, 2000; Bruneel et al., 2010). The patent data, government reports, contract transactions, business reports, etc. could be explored as the supplements. Besides, public demands for frontier technologies and knowledge innovations may contribute to stimulate the transition to knowledge-based economy (Vavakova, 1998; Leydesdorff & Etzkowitz, 2003). The quadruple helix system of universities, the industries, the government and the society based on the social network analysis perspective could be explored in future studies (Park & Park, 2018; Lin & Yang, 2020; Chen et al., 2022; Gallagher et al., 2023).

Although this study does not encompass the most recent years, its primary contributions of the development of a novel methodological framework and the identification of robust core findings across topics and countries, retain enduring relevance. These time-resistant insights continue to offer substantial value to researchers in the field. We will prioritize addressing it in future research.

Considering the delays in database updates, the massive workload of data cleaning, and the rationality and rigor of the overall research methodology, we neglected to update the data to 2024, which is a shortcoming of this study. We will focus on addressing this issue in future research and thank you again for your reminder.

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Declarations

Conflict of interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

- Adams, J. D., Chiang, E. P., & Starkey, K. (2001). Industry-university cooperative research centers. *The Journal of Technology Transfer*, 26, 73–86.
- Ankrah, S., & Omar, A. T. (2015). Universities–industry collaboration: A systematic review. *Scandinavian Journal of Management*, 31(3), 387–408.
- Barringer, B. R., & Harrison, J. S. (2000). Walking a tightrope: Creating value through interorganizational relationships. *Journal of Management*, 26(3), 367–403.
- Benton, T. (2013). Interdisciplinarity and climate change: Transforming knowledge and practice for our global future. *Journal of Critical Realism*, 12(2), 260–265.
- Berahmand, K., Mohammadi, M., Saberi-Movahed, F., Li, Y., & Xu, Y. (2022). Graph regularized non-negative matrix factorization for community detection in attributed networks. *IEEE Transactions on Network Science and Engineering*, 10(1), 372–385.
- Bruneel, J., d’Este, P., & Salter, A. (2010). Investigating the factors that diminish the barriers to university–industry collaboration. *Research Policy*, 39(7), 858–868.
- Chen, H., Song, X., Jin, Q., & Wang, X. (2022). Network dynamics in university–industry collaboration: A collaboration–knowledge dual-layer network perspective. *Scientometrics*, 127(11), 6637–6660.
- Chen, S., Arsenault, C., & Larivière, V. (2015). Are top-cited papers more interdisciplinary? *Journal of Informetrics*, 9(4), 1034–1046.
- Choi, S., Yang, J. S., & Park, H. W. (2015). The triple helix and international collaboration in science. *Journal of the Association for Information Science and Technology*, 66(1), 201–212.
- Compagnucci, L., & Spigarelli, F. (2018). Fostering cross-sector collaboration to promote innovation in the water sector. *Sustainability*, 10(11), 4154.
- Dollinger, M., Coates, H., Bexley, E., Croucher, G., & Naylor, R. (2018). Framing international approaches to university–industry collaboration. *Policy Reviews in Higher Education*, 2(1), 105–127.
- Efi, A. E. (2014). Synergy between academic research and industrialization: The search for development in Nigeria. *Human Resource Management Research*, 4(3), 69–74.
- Egorov, N., Pospelova, T., Yarygina, A., & Klochkova, E. (2019). The assessment of innovation development in the Arctic regions of Russia based on the Triple Helix model. *Resources*, 8(2), 72.
- Eppel, S. (1998). Enhancing markets for climate friendly technologies: Leadership through government purchasing strategies’. *An analysis of measures to promote technological innovation* (Ottawa: prepared by A. Karmali and S. Peck for Technology Issues Table, Climate Change Secretariat, 1999, unpublished).
- Etzkowitz, H. (2002). Networks of innovation: Science, technology and development in the Triple Helix era. *International Journal of Technology Management & Sustainable Development*, 1(1), 7–20.

- Etzkowitz, H. (2003). Innovation in innovation: The Triple Helix of university-industry-government relations. *Social Science Information*, 42(3), 293–337.
- Etzkowitz, H. (2008). *The Triple Helix: University-industry-government innovation in action*. Routledge.
- Etzkowitz, H. (2011). The triple helix: Science, technology and the entrepreneurial spirit. *Journal of Knowledge-Based Innovation in China*, 3(2), 76–90.
- Etzkowitz, H., & Leydesdorff, L. (1995). The Triple Helix–University-industry-government relations: A laboratory for knowledge based economic development. *EASST Review*, 14(1), 14–19.
- Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation: From National Systems and “Mode 2” to a Triple Helix of university–industry–government relations. *Research Policy*, 29(2), 109–123.
- Fan, X., Yang, X., & Chen, L. (2015). Diversified resources and academic influence: Patterns of university–industry collaboration in Chinese research-oriented universities. *Scientometrics*, 104, 489–509.
- Fu, H. Z., & Waltman, L. (2022). A large-scale bibliometric analysis of global climate change research between 2001 and 2018. *Climatic Change*, 170(3–4), Article 36.
- Gallagher, C., Lusher, D., Koskinen, J., Roden, B., Wang, P., Gosling, A., Polyzos, A., Stenzel, M., Hegarty, S., Spurling, T., & Simpson, G. (2023). Network patterns of university-industry collaboration: A case study of the chemical sciences in Australia. *Scientometrics*. <https://doi.org/10.1007/s11192-023-04749-8>
- Glänzel, W., & Schlemmer, B. (2007). National research profiles in a changing Europe (1983–2003) An exploratory study of sectoral characteristics in the Triple Helix. *Scientometrics*, 70(2), 267–275.
- Hamamoto, R., Takasawa, K., Machino, H., Kobayashi, K., Takahashi, S., Bolatkan, A., Shinkai, N., Sakai, A., Aoyama, R., Yamada, M., Asada, K., Komatsu, M., Okamoto, K., Kameoka, H., & Kaneko, S. (2022). Application of non-negative matrix factorization in oncology: One approach for establishing precision medicine. *Briefings in Bioinformatics*, 23(4), Article bbac246.
- Haunschild, R., Bornmann, L., & Marx, W. (2016). Climate change research in view of bibliometrics. *PLoS ONE*, 11(7), Article e0160393.
- Hellsten, I., & Leydesdorff, L. (2016). The construction of interdisciplinarity: The development of the knowledge base and programmatic focus of the journal *Climatic Change*, 1977–2013. *Journal of the Association for Information Science and Technology*, 67(9), 2181–2193.
- Hossain, M. D., Moon, J., Kang, H. G., Lee, S. C., & Choe, Y. C. (2012). Mapping the dynamics of knowledge base of innovations of R&d in Bangladesh: Triple helix perspective. *Scientometrics*, 90(1), 57–83.
- Kafourous, M., Wang, C., Piperopoulos, P., & Zhang, M. (2015). Academic collaborations and firm innovation performance in China: The role of region-specific institutions. *Research Policy*, 44(3), 803–817.
- Kang, W., Zhao, S., Song, W., & Zhuang, T. (2019). Triple helix in the science and technology innovation centers of China from the perspective of mutual information: A comparative study between Beijing and Shanghai. *Scientometrics*, 118, 921–940.
- Kuang, D., Choo, J., & Park, H. (2015). Nonnegative matrix factorization for interactive topic modeling and document clustering. *Partitioned Clustering Algorithms*, 215–243.
- Kwon, K. S., Park, H. W., So, M., & Leydesdorff, L. (2012). Has globalization strengthened South Korea’s national research system? National and international dynamics of the Triple Helix of scientific co-authorship relationships in South Korea. *Scientometrics*, 90(1), 163–176.
- Lavie, D., & Drori, I. (2012). Collaborating for knowledge creation and application: The case of nanotechnology research programs. *Organization Science*, 23(3), 704–724.
- Lee, W. J., & Mwebaza, R. (2022). New strategy for innovative RD&d in view of stakeholder interaction during climate technology transfer. *Sustainability*, 14(14), 8363.
- Lei, X. P., Zhao, Z. Y., Zhang, X., Chen, D. Z., Huang, M. H., & Zhao, Y. H. (2012). The inventive activities and collaboration pattern of university–industry–government in China based on patent analysis. *Scientometrics*, 90(1), 231–251.
- Leydesdorff, L. (2000). The triple helix: An evolutionary model of innovations. *Research Policy*, 29(2), 243–255.
- Leydesdorff, L. (2003). The mutual information of university–industry–government relations: An indicator of the Triple Helix dynamics. *Scientometrics*, 58(2), 445–467.
- Leydesdorff, L. (2011). “Structuration” by intellectual organization: The configuration of knowledge in relations among structural components in networks of science. *Scientometrics*, 88(2), 499–520.
- Leydesdorff, L., & Etzkowitz, H. (2003). Can “the public” be considered as a fourth helix in university-industry-government relations? Report on the Fourth Triple Helix Conference, 2002. *Science and Public Policy*, 30(1), 55–61.
- Leydesdorff, L., & Ivanova, I. A. (2014). Mutual redundancies in interhuman communication systems: Steps toward a calculus of processing meaning. *Journal of the Association for Information Science and Technology*, 65(2), 386–399.

- Leydesdorff, L., & Sun, Y. (2009). National and international dimensions of the triple helix in Japan: University–industry–government versus international coauthorship relations. *Journal of the American Society for Information Science and Technology*, *60*(4), 778–788.
- Leydesdorff, L., & Zhou, P. (2014). Measuring the knowledge-based economy of China in terms of synergy among technological, organizational, and geographic attributes of firms. *Scientometrics*, *98*(3), 1703–1719.
- Li, R., & Fang, W. (2019). University–industry–government relations of the Ministry of Industry and Information Technology (MIIT) universities: The perspective of the mutual information. *PLoS ONE*, *14*(2), e0211939.
- Lin, J. Y., & Yang, C. H. (2020). Heterogeneity in industry–university R&d collaboration and firm innovative performance. *Scientometrics*, *124*(1), 1–25.
- López-Pérez, M. E., Reyes-García, M. E., & López-Sanz, M. E. (2023). Smart mobility and smart climate: An illustrative case in Seville, Spain. *International Journal of Environmental Research and Public Health*, *20*(2), 1404.
- Ma, J., & Yang, D. (2024). Research on the mechanism of government–industry–university–research collaboration for cultivating innovative talent based on game theory. *Heliyon*, *10*(3), Article e25335.
- Mani, S. (2002). *Government, innovation and technology policy: An international comparative analysis*. Edward Elgar Publishing.
- Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Chen, Y., Goldfarb, L., Gomis, M. I., Matthews, J. B. R., Berger, S., Huang, M., Yelekçi, O., Yu, R., Zhou, B., Lonnoy, E., Maycock, T. K., Waterfield, T., Leitzell, K., & Caud, N. (2021). Climate change 2021: The physical science basis. *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, 2.
- McCright, A. M., O’shea, B. W., Sweeder, R. D., Urquhart, G. R., & Zeleke, A. (2013). Promoting interdisciplinarity through climate change education. *Nature Climate Change*, *3*(8), 713–716.
- McLaughlin, J. E., McLaughlin, G. W., McLaughlin, J. S., & White, C. Y. (2016). Using Simpson’s diversity index to examine multidimensional models of diversity in health professions education. *International Journal of Medical Education*, *7*, 1.
- Meissner, D., Cervantes, M., & Kratzer, J. (2018). Enhancing university–industry linkages potentials and limitations of government policies. *International Journal of Technology Management*, *78*(1–2), 147–162.
- Nelson, J. A. (2013). Ethics and the economist: What climate change demands of us. *Ecological Economics*, *85*, 145–154.
- Oreskes, N. (2004). The scientific consensus on climate change. *Science*, *306*(5702), 1686–1686.
- Park, H. W., & Leydesdorff, L. (2010). Longitudinal trends in networks of university–industry–government relations in South Korea: The role of programmatic incentives. *Research Policy*, *39*(5), 640–649.
- Park, H., & Park, H. W. (2018). Research evaluation of Asian countries using altmetrics: Comparing South Korea, Japan, Taiwan, Singapore, and China. *Scientometrics*, *117*, 771–788.
- Paswan, J., Singh, V. K., Karmakar, M., & Singh, P. (2022). Does university–industry–government collaboration in research gets higher citation and altmetric impact? A case study from India. *Scientometrics*, *127*(11), 6063–6082.
- Qian, Y., Liu, Y., & Sheng, Q. Z. (2020). Understanding hierarchical structural evolution in a scientific discipline: A case study of artificial intelligence. *Journal of Informetrics*, *14*(3), Article 101047.
- Richardson, G. (2010). Automated country name disambiguation for code set alignment. In *Proceedings of the 14th European conference on research and advanced technology for digital libraries* (pp. 498–501). Springer-Verlag.
- Santoro, M. D., & Gopalakrishnan, S. (2000). The institutionalization of knowledge transfer activities within industry–university collaborative ventures. *Journal of Engineering and Technology Management*, *17*(3–4), 299–319.
- Sato, S. (2017). Climate change, the built environment and triple-helix innovation. *Energy Procedia*, *143*, 843–850.
- Schillebeeckx, S. J., Chaturvedi, S., George, G., & King, Z. (2016). What do i want? The effects of individual aspiration and relational capability on collaboration preferences. *Strategic Management Journal*, *37*(7), 1493–1506.
- Seppo, M., Rõigas, K., & Varblane, U. (2014). Governmental support measures for university–industry cooperation—Comparative view in Europe. *Journal of the Knowledge Economy*, *5*, 388–408.
- Shaw, R., Pulhin, J. M., & Pereira, J. J. (2010). Climate change adaptation and disaster risk reduction: An Asian perspective. *Community*, *4*(5), 143–169.

- Shenhar, A. J. (1993). The promis project: Industry and university learning together. *International Journal of Technology Management*, 8(6–8), 611–621.
- Shin, J. C., Lee, S. J., & Kim, Y. (2012). Knowledge-based innovation and collaboration: A triple-helix approach in Saudi Arabia. *Scientometrics*, 90(1), 311–326.
- Simpson, E. H. (1949). Measurement of diversity. *Nature*, 163(4148), 688–688.
- Solomon, S., Qin, D., Manning, M., Averyt, K., & Marquis, M. (Eds.). (2007). *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge University Press.
- Song, Y., Fang, Z., & Fu, H. Z. (2023). Influence of interdisciplinarity on scientific impact: The case of climate change field. *Journal of Informetrics*, 17(3), Article 101410.
- Sun, Y., & Cao, C. (2015). Intra-and inter-regional research collaboration across organizational boundaries: Evolving patterns in China. *Technological Forecasting and Social Change*, 96, 215–231.
- Taratori, R., Rodriguez-Fiscal, P., Pacho, M. A., Koutra, S., Pareja-Eastaway, M., & Thomas, D. (2021). Unveiling the evolution of innovation ecosystems: An analysis of triple, quadruple, and quintuple helix model innovation systems in European case studies. *Sustainability*, 13(14), 7582.
- Tijssen, R. J., Van Leeuwen, T. N., & Van Wijk, E. (2009). Benchmarking university-industry research cooperation worldwide: Performance measurements and indicators based on co-authorship data for the world's largest universities. *Research Evaluation*, 18(1), 13–24.
- Vavakova, B. (1998). The new social contract between governments, universities and society: Has the old one failed? *Minerva*. <https://doi.org/10.1023/A:1004384519396>
- Wang, Q., Cao, Z., Xu, J., & Li, H. (2012, Aug). Group matrix factorization for scalable topic modeling. In *Proceedings of the 35th international ACM SIGIR conference on Research and development in information retrieval* (pp. 375–384).
- Wang, Q., & Schneider, J. W. (2019). Consistency and validity of interdisciplinarity measures. *Quantitative Science Studies*, 1(2), 1–28.
- Wang, X., Zhang, S., & Liu, Y. (2021). ITGInsight—discovering and visualizing research fronts in the scientific literature. *Scientometrics*. <https://doi.org/10.1007/s11192-021-04190-9>
- Wang, Y., Li, J., Ning, L., Zeng, D., & Gu, X. (2014). Dynamic patterns of technology collaboration: A case study of the Chinese automobile industry, 1985–2010. *Scientometrics*, 101, 663–683.
- Xu, H. Y., Zeng, R. Q., Fang, S., Yue, Z. H., & Han, Z. B. (2015). Measurement methods and application research of triple Helix model in collaborative innovation management. *Qualitative and Quantitative Methods in Libraries*, 4(2), 463–482.
- Ye, F. Y., Yu, S. S., & Leydesdorff, L. (2013). The triple helix of university-industry-government relations at the country level and its dynamic evolution under the pressures of globalization. *Journal of the American Society for Information Science and Technology*, 64(11), 2317–2325.
- Yoon, J. (2015). The evolution of South Korea's innovation system: Moving towards the Triple Helix model? *Scientometrics*, 104, 265–293.
- Yoon, J., & Park, H. W. (2017). Triple helix dynamics of South Korea's innovation system: a network analysis of inter-regional technological collaborations. *Quality & Quantity*, 51(3), 989–1007.
- Zhang, Y., Chen, K., & Fu, X. (2019). Scientific effects of Triple Helix interactions among research institutes, industries and universities. *Technovation*, 86, 33–47.
- Zhang, Y., Chen, K., Zhu, G., Yam, R. C. M., & Guan, J. (2016). Inter-organizational scientific collaborations and policy effects: An ego-network evolutionary perspective of the Chinese Academy of Sciences. *Scientometrics*, 108(3), 1383–1415.
- Zhu, Z., Cui, S., Wang, Y., & Zhu, Z. (2022). Exploration on the collaborative relationship between government, industry, and university from the perspective of collaborative innovation. *Applied Mathematics and Nonlinear Sciences*, 7(2), 903–912.
- Zyoud, S. H., & Fuchs-Hanusch, D. (2020). Mapping of climate change research in the Arab world: A bibliometric analysis. *Environmental Science and Pollution Research*, 27(3), 3523–3540.

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