The impact of university-industry-government collaboration types on interdisciplinary knowledge integration research: climate change field

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ABSTRACT

Scientific collaboration types constitute pivotal pathways for improving interdisciplinary knowledge integration, transforming traditional knowledge-based economic growth paradigms, and developing new knowledge innovation forces. Based on the triple Helix theory, this study takes the field of climate change, an interdisciplinary field, as an example to construct heterogeneous collaboration networks among universities, industries and governments, analyzing differential impacts of collaboration types on interdisciplinary knowledge integration. Findings reveal universities as core catalysts for interdisciplinary knowledge integration, while actively participate in collaboration with governments and industries. Conversely, governments and industries operating independently or bilateral collaboration demonstrate constrained interdisciplinary knowledge integration capacity, reflecting underdeveloped mutual interest alignment mechanisms. Strategic partnerships with universities may serve as a valuable approach to enhancing their knowledge integration efficacy.

KEYWORDS

University-industry-government collaboration; Interdisciplinary knowledge integration; Interdisciplinarity; Climate change; Triple helix

1. Introduction

The landscape of contemporary knowledge production is undergoing profound structural transformation. Complex issues commonly termed wicked problems, such as climate change, public health crises, and sustainable transitions, transcend the cognitive boundaries and solution capacities of any single discipline (Hellsten & Leydesdorff, 2016; Xu et al., 2016). Within paradigmatic transition, interdisciplinary knowledge integration represents not merely an additive process of knowledge accumulation, but rather a dynamic restructuring and value creation mechanism (Goñi Mazzitelli, 2024). This process facilitates the transcendence of established cognitive frameworks within disciplinary paradigms, enabling a more holistic, dynamic, and adaptive understanding of complex systems. Consequently, interdisciplinary knowledge integration constitutes both intrinsic imperative for academic advancement and a strategic national priority for enhancing scientific capabilities, building competitive advantages, and mitigating systemic risks. This evolution signifies a fundamental transition in knowledge production paradigms, shifting from discipline-oriented to problem driven frameworks (Talbot & Talbot, 2017).

This strategic imperative has been recognized by many counties, elevating collaborative innovation to national priority status (Nelson, 2013; Sato, 2017). For instance, the United States Innovation Strategy, issued by the White House Office of Science and Technology Policy, emphasizes joint initiatives among enterprises, academic institutions, and other social organizations to address critical strategic challenges (The White House Office of Science and Technology Policy, 2010). Published under the European Commission's framework, *Horizon Europe: Strategic Plan 2021-2024* requires transcending disciplinary boundaries while fostering cross-institutional collaboration to confront climate, energy, and transportation challenges (Europe Commission, 2021). Formulated through the Council for Science, Technology and Innovation in Japan, the *Sixth Science, Technology and Innovation Basic Plan* advocates establishing co-created emerging industries, emphasizing demand-driven collaboration and risk management between universities, research institutions, and enterprises (Government of Japan, 2021). In addition, enacted under Chinese legislative system, policies including the *Science and Technology Progress Law*, *Commercialization of Scientific Achievements Act*, and *14th Five-Year Plan* systematically position integrated innovation as central to scientific advancement (National People's Congress Standing Committee, 2021). The "New Quality Productive Forces" has been prioritized in China recently, with an emphasis placed on the integration of scientific innovation resources and the establishment of collaborative framework spanning fundamental research, technological breakthroughs, and industrial application (Ren & Guo, 2025).

Within single type of entity, such as universities or research institutes, knowledge structures tend toward homogeneity, lacking the sufficient heterogeneity and complementarity to drive authentic integrative innovation (Vienni-Baptista & Pohl, 2024). University-industry-government (UIG) collaboration demonstrate distinctive function by systematically overcoming fundamental obstacles to interdisciplinary knowledge integration while providing essential enabling mechanisms and resource foundations from three perspectives. (1) Through partnerships such as joint labs and innovation platforms, UIG collaborations break down traditional barriers and create shared spaces where people from different disciplines and institutions can continuously exchange knowledge. (Hossain et al., 2012; Nurzal & Rosadi, 2022). (2) It synthesizes heterogeneous resources to catalyze integration, effectively integrating distinct repositories of knowledge, technologies, research perspectives, and resources (data, equipment, funding, market insights) from diverse institutions. This synergy produces new integrated knowledge, comprehensive solutions, and even emerging interdisciplinary fields capable of tackling complex challenges. (Etzkowitz, 2002, 2011; Lavie & Drori, 2012; Schillebeeckx et al., 2016; Zhang et al., 2019). (3) By engaging stakeholders from academia, industry, and government, UIG collaborations reframe complex problems through multiple lenses. This shifts problem-solving from narrow approaches to systemic frameworks, guiding interdisciplinary integration and preventing oversimplification of issues like climate change. (Albats, 2018; Grimm & Reinecke, 2024).

While existing research has achieved considerable depth in examining the collaborative types (Etzkowitz & Leydesdorff, 2000; Xiong et al., 2025; Wang et al., 2024) and measurement methodologies for interdisciplinary integration (Zhang et al., 2016; Leydesdorff, 2018; Rousseau, 2019), exploration of the relationship and operational mechanisms between these two critical dimensions remains underdeveloped. Specifically, although some studies acknowledge the potential facilitative role of collaboration in knowledge integration (Lai & Su, 2024), the question of how different collaborative innovations shape the depth, breadth, and novelty of interdisciplinary knowledge integration remains inadequately addressed. This insufficient mechanistic understanding impedes precise identification of optimal collaborative configurations for knowledge integration.

To address this gap, this study takes the climate change as a representative field requiring interdisciplinary knowledge integration (Fu & Waltman, 2022; Xiong et al., 2023), addressing the core research question: How do different types of collaborative innovation influence the effectiveness of interdisciplinary knowledge integration? The findings aim to provide evidence-based guidance for research management on selecting and organizing collaboration types to enhance interdisciplinary knowledge integration.

2. Literature review

2.1. Interdisciplinary knowledge integration

The process of knowledge integration includes identifying knowledge units within heterogeneous network resources and synthesizing novel forms through extraction, transformation, and integration to address complex problems (Song et al., 2022). Correspondingly, interdisciplinary knowledge integration involves extracting, matching, integrating, refining, and processing knowledge from two or more disciplines, culminating in transformative synthesis that generates new knowledge capable of addressing complex challenges. Hacklin et al. (2009) conceptualized knowledge integration as co-evolutionary spillover effect occurring across disconnected knowledge fields and dissolving disciplinary boundaries. Rafols and Meyer (2010) indicated that interdisciplinary is the integration of different knowledge systems. Fan et al. (2019) indicated that disciplinary integration is an advanced iteration of interdisciplinary research. Knowledge integration across disciplinary boundaries serves as the primary engine for generating novel knowledge and solutions (Bu et al., 2021; Sheng et al., 2023; Zhang et al., 2024), facilitating reconfiguration of knowledge frameworks (Zhang & Zhang, 2020). For instance, transformative discoveries in fields ranging from quantum computing to synthetic biology have fundamentally reconfigure scientific frontiers.

Citation represents significant mechanisms facilitating disciplinary integration and subsequent knowledge innovation. Numerous studies used citation counts to quantify interdisciplinary knowledge flows within publications as typical measurement for integration intensity (Song et al., 2018). Okamura (2019) identifies interdisciplinary citation as fundamental to knowledge growth and innovation. Karunan et al. (2017) employ directed interdisciplinary citations to quantify knowledge contributions among different disciplines. Chakraborty (2018) proposed the diversity index based on proportions of interdisciplinary references, conceptualizing interdisciplinary knowledge integration as the process of absorption, internalization, and output. Based on the theories from disciplines such as biology, information science, economics, network science, physics, and science of science, a complete set of interdisciplinarity indicators has gradually been formed used for measuring the degree of interdisciplinary knowledge integration and methods. Variety, balance and disparity respectively characterize three distinct dimensions of interdisciplinary research (Stirling, 2007):

- **Variety** quantifies the number of categories into which system elements, indicating disciplinary richness (McIntosh, 1967) through metrics including the Hill Type (Hill, 1974) and Cited Outside Category (Porter & Chubin, 1985).
- **Balance** measures the distributional equity of disciplinary contributions through indicators (Pielou, 1977) such as Shannon entropy (Shannon, 1948), Brillouin index (Brillouin, 1956), Gini coefficient (Gini, 1921), and Herfindahl-Hirschman index (Aristodemou & Tietze, 2018).
- **Disparity** refers to the degree in which the elements may be distinguished (Runnegar, 1987), in other words, assessing the distance between disciplines using metrics like Cosine (Thijs, 2021) and Salton (Rafols, 2014).

Stirling (2007) integrated the three dimensions into the Rao-Stirling index, enabling multidimensional quantification of interdisciplinarity. Leydesdorff (2018) proposed diversity index (DIV) by introducing the Gini coefficient on this index, refining the diversity measurement. Rousseau (2019) proposed the DIV* metric to address the limitation of small numerical values inherent in the DIV metric. Consequently, this study employs both the composite index and its three basic properties - variety, balance, and disparity indicators to measure interdisciplinary knowledge integration in the field of climate change.

2.2. Triple Helix of university – industry – government interactions

Scientific collaboration refers to cooperative frameworks wherein diverse entities leverage complementary competencies to achieve resource integration, risk sharing, capability complementarity, and common aims (Cosenz, 2022). It is benefit to enhance innovation vitality and potential significantly, improve the efficiency and quality of scientific outputs, and provides support for national strategic and sustainable development (Miller et al., 2018). Etzkowitz and Leydesdorff (1995) pioneered the Triple Helix theory, conceptualizing the dynamic spiral configuration among three entities during innovation processes, namely university (U), industry (I), and government (G). Universities serve as primary entities for knowledge production and dissemination, leveraging their resource advantages and expertise to generate cutting-edge research and transfer outcomes across other sectors (Lavie& Drori, 2012; Schillebeeckx et al., 2016). Industries, functioning as critical roles in global value chains, drive innovation through proprietary research and commercialization of academic discoveries (Etzkowitz, 2011; Zhang et al., 2019). Within interdisciplinary knowledge integration systems, governmental actors transcend their traditional roles by providing strategic coordination and organizational facilitation (Lepori et al., 2007; Etzkowitz, 2002). Beyond research funding, governments make regulatory frameworks and implement incentive mechanisms to catalyze knowledge translation and industrial innovation, mitigating sectoral risks while fostering inclusive innovation ecosystems.

These entities engage in spiral types of interaction while maintaining institutional autonomy for enhancing academic innovation capabilities, accelerating industrial technological advancement, and optimizing governance efficacy (Etzkowitz & Leydesdorff, 2000). The theory employs information theory metrics including Shannon entropy and mutual information, particularly mutual information, to quantify synergistic effects emerging from trilateral interactions (Leydesdorff & Etzkowitz, 1998; Ye et al., 2013). This theory has been widely used in studies of the knowledge-based economy and innovation (Leydesdorff, 2006; Leydesdorff & Zhou, 2014; Park & Leydesdorff, 2010).

The Triple Helix theory provides a robust research perspective with the complementary functional advantages in driving interdisciplinary knowledge integration for analyzing collaborative dynamics among universities, industries, and governments. It can be used to capture how the interactions of these entities catalyze transformative knowledge integration processes inaccessible to any single sector. In this study, the publications in the field of climate change will be categorized into seven mutually exclusive sub-datasets based on institutional affiliations: single-institution (U, I and G) and inter-institution collaborations (UI, UG, IG, and UIG). This classification scheme can examine how combinations of participants from different institutions affect the variety, balance, and disparity of interdisciplinary knowledge integration.

2.3. The relationship between UIG collaboration types and interdisciplinary knowledge integration

Inter-institutional collaboration creates enabling conditions for knowledge integration by facilitating the integration of researchers with diverse disciplinary backgrounds, thereby promoting the interdisciplinary dissemination, circulation, exchange, and sharing of knowledge. Empirical studies confirm that increased researcher heterogeneity within collaborative teams enhances the diversity of resources, including terminology, methodologies, and datasets, elevating research quality and scientific impact (Freeman & Huang, 2014). In other words, working in universities, firms or governmental organizations increases the propensity of interdisciplinary collaborations (Van Rijnsoever & Hessels, 2011).

Nevertheless, current academic research on the influence of scientific collaboration models on interdisciplinary knowledge integration remains nascent. Wang (2015) demonstrates that international collaboration enhances interdisciplinary research, with variations observed in different research fields. Zhang et al.'s (2018) analysis of highly cited scholars in Social Sciences further reveals that institutional partnerships with diverse disciplinary backgrounds facilitate knowledge integration. Case studies by Chen et al. (2020) on Tsinghua University's joint institute with Toyota Motor Corporation illustrate how specialized interdisciplinary programs catalyze UI knowledge integration, proving essential for addressing complex urban challenges. The interdisciplinary research team at Monash University in Australia indicated that sustained engagement among researchers, policymakers, and industry practitioners serves as a critical driver for inter-institutional collaboration. Sworowska-Baranowska (2022) indicated that the establishment of formal collaborative agreements among diverse institutions facilitates the advancement of interdisciplinary research initiatives, but interdisciplinarity does not offer significant stimulation for inter-institutional collaboration. Xiong et al.'s (2023) examination of co-authorship types among different institutions in climate change research delineates synergistic interaction effects within this typical interdisciplinary field. Koschatzky's (2002) analysis of Slovenian innovation survey data identifies institutional scale and research capacity as key determinants of knowledge integration efficacy across diverse collaboration types.

Generally, existing research has established the significance of scientific collaboration and interdisciplinary knowledge integration. However, a mechanistic black box remains regarding how different collaborative types enable integration processes. Although citation-based metrics (e.g., Rao-Stirling index) quantify interdisciplinary knowledge integration, and the Triple Helix framework identifies institutional functions, the pathways linking collaboration types to integration mechanisms remain unclear.

To address this issue, this study utilizes a granular classification of U–I–G (university–industry–government) collaboration types capture how institutional role complementarity (U: theoretical innovation; I: technical translation; G: institutional scaffolding) shapes interdisciplinary knowledge integration effects. It further explores how different collaboration types influence the variety, balance, and disparity of climate change research.

3. Research design

Universities, industries, and governments exhibit divergent capacities for advancing interdisciplinary knowledge integration because of variations in institutional functions, talent structures, organizational frameworks, and operational logics. Universities accommodate researchers across diverse disciplines, possessing distinctive advantages including talent resources, cutting-edge disciplinary knowledge, flexible organizational structures, and permissive academic environments conducive to interdisciplinary knowledge integration. In contrast, industrial and governmental entities possess substantial technological resources, funding, and policy leverage, with limitations in interdisciplinary talent due to specialized operational mandates. Collaborative engagement with academic institutions may effectively mitigate this deficiency. Interdisciplinary knowledge integration is affected by institutional attributes and collaboration types.

This study established a three-tiered analytical framework, including comparative analysis of institutional capacities, comparative analysis of collaboration types, strategy optimization, to progressively investigate: (1) the interdisciplinary knowledge integration capacities of single-institutions; (2) the effect of different collaboration types on the interdisciplinary knowledge integration; and (3) optimal collaboration strategies for heterogeneous entities. This study proposes the following research questions and hypotheses, with the theoretical framework illustrated in Fig. 1.

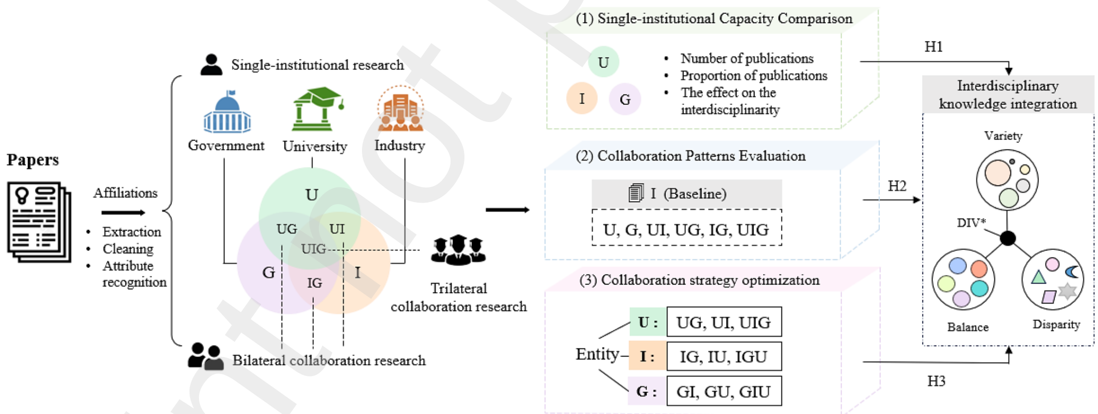

Fig. 1. Research framework.

Research Question 1 (RQ1). Do universities demonstrate superior efficacy in enhancing interdisciplinary knowledge integration compared to industries or governments within single-institution configurations?

To empirically investigate this question, hypothesis 1 (H1) was proposed that universities generate scientific outputs exhibiting significantly higher interdisciplinarity than those produced solely by I or G. Based on the three dimensions of comprehensive interdisciplinary nature, three hypotheses can be further proposed. Compared to the industrial and government entities, universities generate research publications with stronger disciplinary variety (H1a), higher disciplinary balance (H1b), .greater disciplinary disparity (H1c).

Research Question 2 (RQ2). Does inter-institutional collaboration significantly enhance interdisciplinary knowledge integration relative to single-institutional research? Theoretical foundations indicate that interdisciplinary research emerges from heterogeneous team collaborations, where diversity in methodologies facilitates knowledge recombination (Abramo et al., 2018). Specifically, collaboration enables researchers with disparate disciplinary perspectives, cognitive models and methodological approaches to converge on complex problems, constituting the core mechanism of interdisciplinary knowledge integration.

Based on the seven collaboration types of U, I and G, this study takes the publications produced by industry as the baseline against which the remaining six collaborative types are evaluated. The second hypothesis (H2): Relative to the publications from industry, publications from other collaborative types exhibit statistically significant enhancements in interdisciplinary knowledge integration degree. Sub-hypotheses specify the multidimensional nature of interdisciplinary knowledge integration: Inter-institutional collaborative publications demonstrate increased disciplinary variety (H2a), disciplinary balance (H2b), and Inter-institutional collaborative publications enhance disciplinary disparity (H2c).

Research Question 3 (RQ3). From the perspective of U, I, and G respectively as primary scientific research institutions, which collaboration types maximize interdisciplinary knowledge integration efficacy? The theory of Triple Helix theoretical indicates that synergistic tripartite engagement among U, I, and G generates non-linear innovation dynamics to optimize societal value creation (Datta et al., 2019; Zhou & Wang, 2023). Complementarily, Mode 2 knowledge production theory emphasizes that heterogeneous organizational structures incorporating multi-institution stakeholders enhance interdisciplinary knowledge integration capacity (Lenhard et al., 2006).

This study conducts institution-specific analyses for U, I, and G to examine relationship between UIG collaborative types and interdisciplinary knowledge integration efficacy. We propose Hypothesis 3 (H3): Trilateral UIG collaboration demonstrates significantly greater interdisciplinary knowledge integration efficacy than bilateral collaboration types, with superiority measurable across three subdivided dimensions: enhanced disciplinary variety (H3a), balance (H3b), and disparity (H3c).

4. Method

4.1. Data

Data are retrieved from the Web of Science Core Collection, including both the Science Citation Index Expanded (SCI-E) and Social Sciences Citation Index (SSCI) databases. Utilizing bibliometric retrieval strategies established in the field of climate change scholarship (Zyoud & Fuchs-Hanusch, 2020; Fu & Waltman, 2022; Song et al., 2023), articles and reviews manifesting the lexicographic constructs "climate chang*", "climate variabilit*", "global warming", and "climate warming" within title/abstract from 2001 to 2021 were extracted. The retrieval framework excludes articles and the records lack of institutional affiliation metadata. Following comprehensive post-retrieval deduplications and exclusion of articles labeled with retraction, a total of 194,954 articles were collected as sample, thereby constituting the foundation of empirical analysis.

To delineate institutional collaboration networks in climate change research, this study used the ITGInsight software to extract and standardize institutional metadata from author affiliations (Wang et al., 2021). Subsequently, the process of data cleaning was performed through embedded text similarity computation algorithms of this software combined with manual verification to ensure metadata accuracy. Guided by the Triple Helix theory, institutions were classified into three categories: academic institutions (U) including universities and non-governmental research institutes; industrial entities (I) encompassing corporations, industry associations, foundations, and non-governmental conservation organizations; and governmental entities (G) comprising state agencies, verified governmental research institutes, and United Nations agencies.

Through rigorous multiple rounds of manual retrieval, cleaning, and identification, 50,403 unique institutions were classified, achieving a mean institutional recognition rate of 96.07% across the database, calculated as the ratio of classified institutions to total affiliations per publication.

4.2. Variables

This section details the variables of regression analysis. Interdisciplinary knowledge integration serves as the dependent variable, operationalized through the DIV* index and its three sub-dimensions (variety, balance, disparity). The independent variable comprises seven UIG collaboration types based on Triple Helix theory. Control variables are established through empirical precedents to mitigate confounding influences.

4.2.1. Indicators of interdisciplinarity

Interdisciplinarity (Diversity) and its three basic attributes includes variety, balance and disparity. Variety indicates the number of categories within a system, balance quantifying the distributional uniformity across categories; and disparity measuring the pairwise dissimilarity of system elements based on categorical heterogeneity. The jcitnetw and mode2div software developed by Leydesdorff's team were used to compute the interdisciplinary knowledge integration indicators for each publication based on bibliographic references. These metrics serve as dependent variables in this research, with computational formulas detailed in Table 1.

Table 1
Formula for calculating interdisciplinary indicators.

Name	Formula	Explanation
DIV*	$DIV_c^* = n_c[1 - G(c)]\left[\sum_{i,j=1;i\neq j}^{i=n_c,j=n_c} \frac{d_{ij}}{n_c(n_c-1)}\right]$	n_c denotes the number of categories represented in the references of target document c, G(c) represents the Gini coefficient measuring distributional inequality, and d_{ij} indicates the cosine distance between disciplines i and j.
Variety	$Variety_c = \frac{n_c}{N}$	N denotes the complete set of disciplinary categories covered by references across all publications in the dataset.
Balance	$Balance = 1 - Gini_c = 1 - \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\|x_i - x_j\|}{2n^2\bar{x}}$	x_i and x_jx_i and x_j represent the respective counts of references classified under disciplinary categories i and j.
Disparity	$Disparity_c = \sum_{i,j=1;i\neq j}^{i=n_c,j=n_c} \frac{d_{ij}}{n_c(n_c-1)}$	d_{ij} indicates the disciplinary distance between fields i and j, normalized by the factor $n_c(n_c-1)$, where n_c represents the number of disciplinary categories in the target document's references.

Note：The substantial sample size in this study resulted in small values for both variety and balance metrics. To facilitate subsequent regression analysis and enhance model interpretability, these metrics were multiplied by 100,000 and 100 respectively. Robustness checks confirmed that the scaled metrics preserved original correlation types, non-parametric test outcomes, and regression model significance without altering statistical interpretations.

4.2.2. The type of UIG collaboration

Focusing on micro-level institutional collaborative relationships, bibliometric indicators quantifying the number or proportion of UIG collaborative publications serve as fundamental metrics for assessing the intensity of interactions (Tijssen et al., 2009). This study operationalizes UIG collaboration type as a categorical independent variable. Specifically, publications are classified into seven distinct types based on institutional attributes:

(1) Single-institution publications: U (university), I (industry), G (government)

(2) Bilateral collaboration publications: UI (university-industry collaboration), UG (university-government collaboration), IG (industry-government collaboration),

(3) Trilateral collaboration publications: UIG (tripartite university-industry-government collaboration).

4.2.3. Control variables

To eliminate potential confounding effects on interdisciplinarity, this study incorporates established control variables indicated by previous literature. First, team size may affect interdisciplinarity of climate change research. While larger research teams potentially facilitate interdisciplinary knowledge integration through the incorporation of researchers with diverse disciplinary expertise, opposing perspectives contend that cognitive friction inherent in such collaborations may impede the integration process (MacLeod, 2018). Therefore, a team characteristic variable (n_authors) will be considered as a control variable. Second, the scale of participating entities, measured by the number of countries (n_countries), requires control in analyses of interdisciplinarity (Cassi et al., 2014). Other publication characteristics were incorporated as control variables in the analytical framework such as article length (Pages), document type (doc_type) and publication year (pub_year) (Song et al., 2023).

Given the extensive scope and heterogeneity of climate change research topics, significant variations exist in interdisciplinary characteristics across different topics. To mitigate the systematic influence of topic attributes on interdisciplinary knowledge integration, this study conducted topic modeling on climate change publications, subsequently incorporating identified topics as dummy variables into regression models. The analytical corpus comprised titles, abstracts, keywords, and expanded keywords from each publication. Following initial data cleaning, bigrams and trigrams were generated from high-frequency conjunctions. Textual features were then vectorized using TF-IDF weighting to construct a term-document matrix. Subsequent non-negative matrix factorization (NMF) decomposition identified eight topics (Kuang, Choo, & Park, 2014), including climate simulation model, climate technology, biodiversity, agriculture, physical science basis, paleoclimatology, climate policy, and vegetation (see the Appendix). Each publication was ultimately assigned to its dominant topic category based on NMF.

4.3. Estimation methods

In order to investigate the relationship between UIG collaboration types and interdisciplinary knowledge integration at the publication level, ordinary least-squares linear (OLS) regression with robust standard errors was utilized in Stata 21.0. Separate regression analyses were conducted for composite interdisciplinary knowledge integration and its constituent dimensions comprising diversity, balance, and disparity to enable sequential hypothesis testing.

5. Results

5.1. Descriptive statistics

5.1.1 Trends of publications published by various institutions

The number of annual publications and the proportions of seven different collaboration types have been illustrated in Fig. 2. Universities serve as the pioneering force driving climate change research, with independent publications accounting for 66.93% of annual publications, exceeding industrial (1.2%) and governmental (5.0%) publications, while exhibiting exponential growth (from 950 publications in 2001 to 19,671 in 2021). Although governmental publications demonstrated phased growth during 2001-2011, their proportions displayed volatile decline after 2003, reflecting an institutional transition from direct knowledge production toward scientific collaboration. Industries maintained minimal independent outputs with progressively diminishing shares, indicating growing reliance on collaboration types for research resource acquisition.

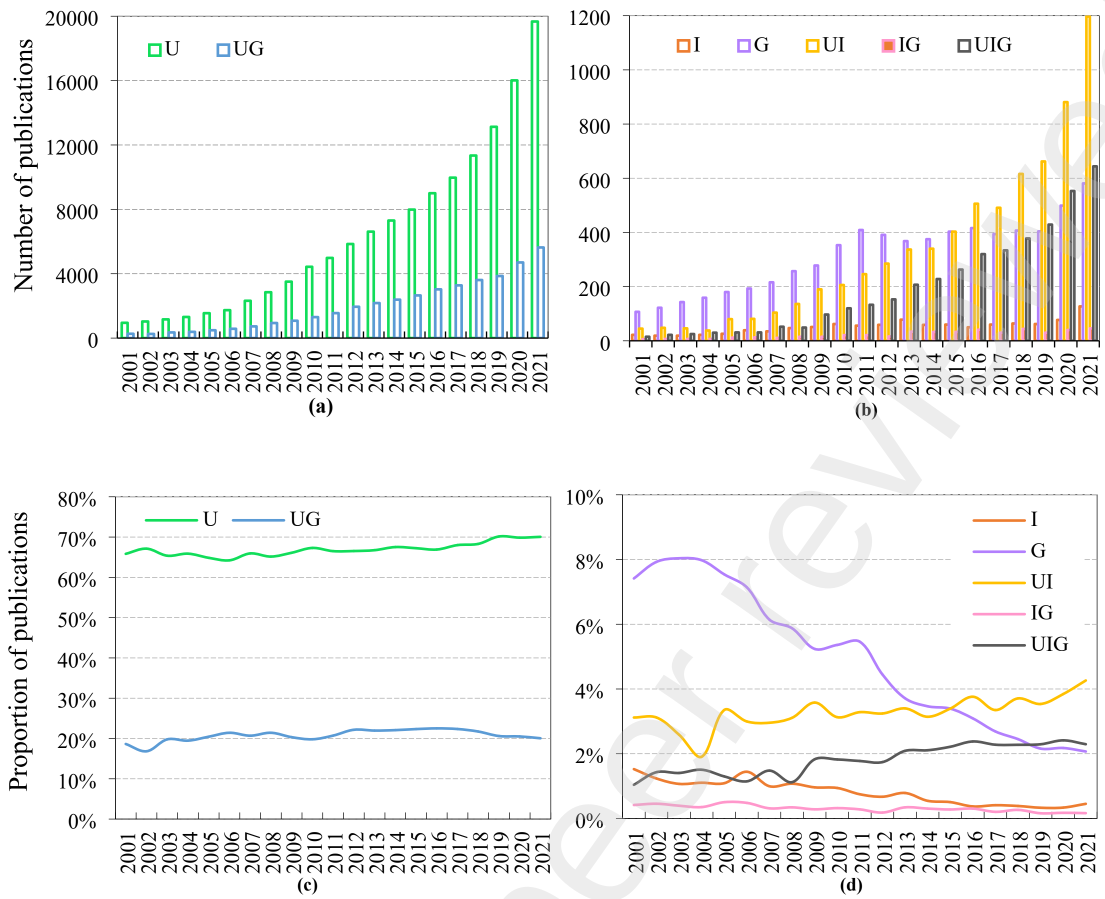

Fig. 2. Trends of publications published by various institutions.

Inter-institutional collaborations exhibit distinct evolutionary trajectories (Fig. 2). UG collaborations constitute the predominant type (≈ 20% of total publications), reflecting governmental reliance on academic expertise for evidence-based policymaking and risk assessment. This relationship enables interdisciplinary knowledge co-production where scientific rigor informs regulatory frameworks while policy priorities shape research agendas (Zhao et al., 2015). UI collaborations display gradual but fluctuated ascent, reflecting industry's strategic absorption of R&D capabilities through acquiring commercial technologies and technical talents, thereby enabling interdisciplinary innovation. Conversely, IG partnerships remain persistently constrained by divergent priorities: industry focuses on commercial value while government prioritizes the aim of maximizing public interest. This fundamental misalignment inhibits the development of effective collaboration mechanisms.

Notably, publications from UIG collaboration surged nearly 20 times (from 1,443 publications in 2001 to 28,080 in 2021). This phenomenon demonstrates emergent inter-institutional and interdisciplinary collaboration platforms that integrate interdisciplinary knowledge innovation capacity of universities, technology transfer and problem-solving capability of industry, and normative authority of governments. It also reveals that universities are evolving from traditional knowledge producers into dynamic societal innovation centers that catalyze inter-institution collaboration by integrating I and G into their knowledge production ecosystems.

5.1.2 Trends of UIG collaboration networks

This study utilized both panoramic and schematic network visualization methods to elucidate institutional collaboration dynamics. The panoramic network visualization constructed by excluding intra-system collaborations within the Triple Helix framework, representing individual institutions as nodes whose size scales proportionally to degree centrality, thereby comprehensively visualizing inter-institutional collaboration types. The schematic network visualization simplifies micro-level complexity of institution collaborations and retains collaboration types, consolidating institutions into three meta-nodes (U, I, and G), where node size corresponds to publication numbers and edge reflects collaboration frequency in Fig. 3.

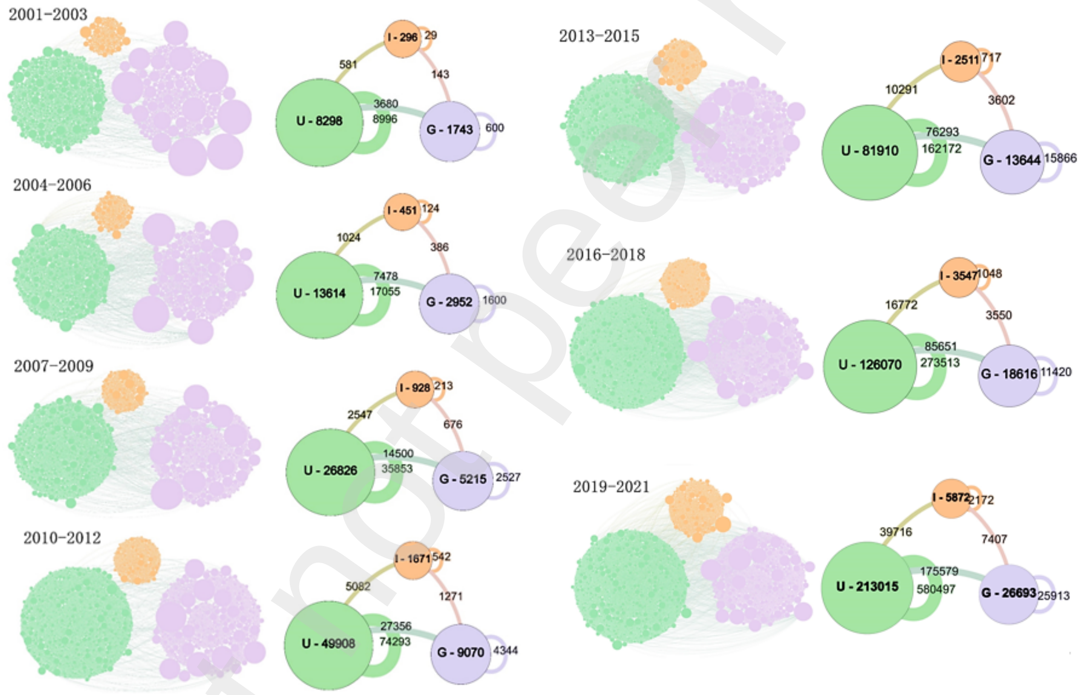

Fig. 3. Evolution of heterogeneous UIG collaboration networks based on triple helix theory.

Within the UIG collaboration networks, nodes exhibiting the highest degree centrality consistently emerged among governments during early stages, while universities demonstrated relatively lower average centrality. This type manifested as a pronounced dominance of few governmental actors in collaborative networks, with agencies such as the United States Forest Service (USFS) recording the highest degree and betweenness centrality during 2001-2003. Subsequently, centrality metrics gradually balanced between governments and universities, indicating broader participation that diminished monopolistic positions. For instance, the United States National Oceanic and Atmospheric Administration (NOAA) dominated in 2007-2009, the French National Center for Scientific Research (CNRS) achieved peak centrality from 2020 to 2015;

and The Spanish National Research Council (CSIC) was the biggest node in 2016 – 2021, all of which are governments. The betweenness centrality of China's Chinese Academy of Sciences (CAS) ascended from 12th in 2001-2003 to 2nd in 2019-2021, signifying its growing brokerage role.

The Triple Helix collaboration network exhibits significant structural intensification over time, evidenced by the progressive rise in average degree from 2.68 to 9.40. This phenomenon signals enhanced interdisciplinary scientific collaboration efficiency among U, I and G through accelerated knowledge recombination and resource integration mechanisms. Beyond overall connectivity, the nature of these relationships has also grown more cohesive. This is evidenced by an increasing average clustering coefficient, signaling the formation of denser local research clusters, alongside a decreasing average path length, which indicates more efficient links between disparate parts of the network. This dual trend of greater local density paired with shorter global distances reveals the gradual emergence of small-world characteristics within the Triple Helix collaboration landscape.

5.1.3 Trends of interdisciplinarity

Fig. 4 shows the interdisciplinarity evolution of climate change research. The diversity of climate change research exhibits a fluctuating yet slightly ascending trend across the 2001-2021 period. After an initial rise-decline phase (2001-2004), it entered sustained growth, rising from 18.84 to 31.62. The three sub-dimensional metrics reveal distinctive evolutionary types. The rising variety indicates increasingly diverse knowledge foundations, with climate studies incorporating broader disciplinary perspectives. The balance has remained relatively unchanged, indicating that the proportional representation of supporting disciplinary knowledge in climate change research is stable. The sustained growth of disparity reflects increasingly intensified engagement with cognitively distant disciplines.

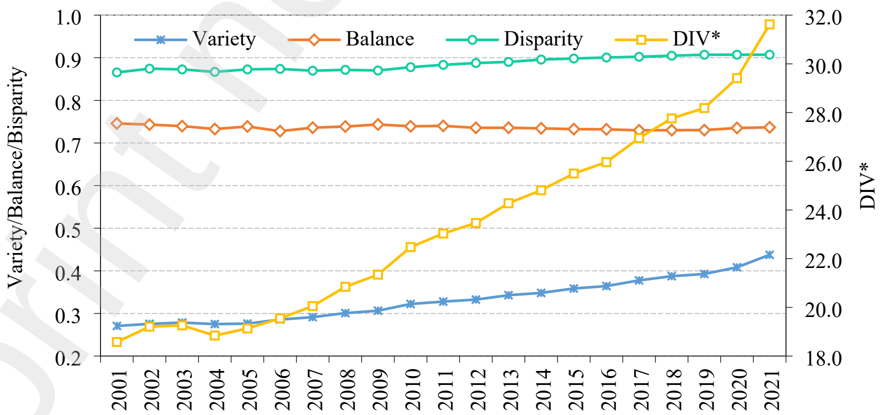

Fig. 4. Trends of interdisciplinarities.

5.1.4 Correlation analysis

Table 2 reports the results of the Pearson correlations. The results indicate significant weak correlations between control variables and core independent variables, while control variables correlations remain moderate (with coefficients ranging from 0.02 to 0.42, $p < 0.05$). Specifically, balance exhibits significant negative correlations with the number of countries, authors, and pages, whereas other variables demonstrate positive correlations. The multicollinearity testing via variance inflation factor (VIF) analysis confirmed all VIF values were below the threshold of 10, demonstrating the absence of severe multicollinearity among the variables, including those for collaborative innovation models.

Table 2

Correlation coefficients of variables.

Variables	DIV*	Variety	Balance	Disparity	n_countries	n_authors	Pages
DIV*	1						
Variety	.945**	1					
	0.000						
Balance	.210**	-.035**	1				
	0.000	0.000					
Disparity	.329**	.260**	-.089**	1			
	0.000	0.000	0.000				
n_countries	.084**	.112**	-.123**	.067**	1		
	0.000	0.000	0.000	0.000			
n_authors	.064**	.087**	-.172**	.164**	.413**	1	
	0.000	0.000	0.000	0.000	0.000		
Pages	.351**	.423**	-.168**	.067**	.055**	.027**	1
	0.000	0.000	0.000	0.000	0.000	0.000	

Note: ***p<0.01, ** p<0.05, * p<0.1.

This study implemented Kruskal-Wallis H nonparametric testing to evaluate differential effects across collaboration types on interdisciplinary knowledge integration, revealing statistically significant disparities in DIV* ($H = 1001.784$, $p < 0.001$), variety ($H = 1180.891$, $p < 0.001$), balance ($H = 2520.975$, $p < 0.001$), and disparity ($H = 1257.174$, $p < 0.001$). Subsequent Bonferroni-adjusted pairwise comparisons confirmed robust performance differentials among different collaboration types.

5.2. The impact of university-industry-government collaboration types on knowledge integration

5.2.1. The effect of single-institutional research on interdisciplinary knowledge integration

In this study, Ordinary Least Squares (OLS) regression was used to estimate single-institutional research effects on interdisciplinary knowledge integration. The basic regression model is specified as follows:

$$Y_i = \alpha + \beta Institution_i + \gamma X_i + u_i$$

Where Y_i denotes the degree of interdisciplinary knowledge integration measured by the DIV* indicator and the three constituent sub-dimensions (variety, balance and disparity). $Institution_i$ represents the type of institution (U/I/G). X_i represents control variables including the number of authors, the number of countries, page length, publication year, and document type and u_i is the stochastic error term. Regression analyses incorporated robust standard errors to address heteroscedasticity, with all continuous variables subjected to winsorization at the 1% and 99% quantiles to mitigate distortion from extreme values.

As demonstrated in Models 1-3 (Table 3), U demonstrates significantly greater influence on interdisciplinary knowledge integration compared to single-institutional research from I or G, with publications exhibiting DIV* values 1.97 units higher than I or G. Conversely, single-institutional research produced by G or I prove less effective in advancing interdisciplinarity, validating hypothesis 1 (H1). The divergence in the degree of interdisciplinary knowledge integration among different institutions originates in fundamentally distinct institutional functions and innovation imperatives. For U, the primary knowledge production centers on pioneering novel knowledge through interdisciplinary collaboration. As evidenced in previous research (Zhang et al., 2016; Taratori et al., 2021), interdisciplinary knowledge integration is benefit to scientific breakthroughs by recombinant innovation across disconnected knowledge fields. In addition, U allocate disproportionately greater resources to high-risk and high-reward interdisciplinary initiatives compared to other entities, reflecting their institutional prioritization of frontier knowledge exploration.

Industries affected by market-driven factors so that prioritize applied technological translation. Industries prioritize applied technological translation due to market-driven imperatives. Their R&D investments systematically target specialized knowledge frontiers with clear commercialization pathways. This strategy minimizes R&D cycle times while maximizing returns on innovation investments, thereby diminishing engagement with interdisciplinary knowledge integration. Governments, constrained by departmental mandates and public accountability mechanisms, exhibit risk-averse willingness and preference for research on inherited knowledge. They emphasize incremental advances within established paradigms rather than disruptive interdisciplinary exploration.

Models 4-12 reveal relationships between U/I/G independent research and the three constituent sub-dimensions of interdisciplinarity (Table 3). Both variety (H1a) and disparity (H1c) demonstrate statistically significant positive correlations with U independent research (coefficient = 0.229, p<0.01 and coefficient = 0.024, p<0.01 respectively). But the dimension of balance (H1b) exhibits inverse relationship (coefficient = -1.276, p<0.01), rejecting initial hypothesis. This finding suggests core disciplines continue to dominate interdisciplinary knowledge integration in climate change research. The statistical advantages of these core disciplines create the phenomenon of imbalance, which enhances integration efficiency through expertise concentration, but may come at the cost of limiting innovative restructuring in peripheral areas. This pattern potentially reflects the path dependence of research in this field: while the necessity of interdisciplinary knowledge integration is increasingly acknowledged, established disciplinary frameworks still impose constraints on disruptive inquiry.

Table 3
Benchmark Regression results.

Variables	DIV*			Variety			Balance			Disparity		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
I	-4.283***			-0.499***			4.401***			-0.084***		
	(0.368)			(0.053)			(0.373)			(0.006)		
G		-1.530***			-0.177***			0.705***			-0.013***	
		(0.145)			(0.022)			(0.150)			(0.001)	
U			1.973***			0.229***			-1.276***			0.024***
			(0.137)			(0.020)			(0.141)			(0.002)
n_countries	0.694***	0.666***	0.651***	0.129***	0.126***	0.124***	-0.689***	-0.682***	-0.665***	0.002***	0.002***	0.001***
	(0.045)	(0.045)	(0.045)	(0.007)	(0.007)	(0.007)	(0.040)	(0.040)	(0.040)	(0.000)	(0.000)	(0.000)
n_authors	0.096***	0.098***	0.096***	0.019***	0.019***	0.019***	-0.381***	-0.384***	-0.383***	0.004***	0.004***	0.004***
	(0.014)	(0.014)	(0.014)	(0.002)	(0.002)	(0.002)	(0.013)	(0.013)	(0.013)	(0.000)	(0.000)	(0.000)
Pages	0.734***	0.735***	0.734***	0.132***	0.132***	0.132***	-0.335***	-0.336***	-0.335***	0.000***	0.000***	0.000***
	(0.007)	(0.007)	(0.007)	(0.001)	(0.001)	(0.001)	(0.006)	(0.006)	(0.006)	(0.000)	(0.000)	(0.000)
Doc_type	1.218***	1.219***	1.219***	0.271***	0.271***	0.271***	-1.111***	-1.111***	-1.112***	0.002***	0.002***	0.002***
	(0.021)	(0.021)	(0.021)	(0.003)	(0.003)	(0.003)	(0.017)	(0.017)	(0.017)	(0.000)	(0.000)	(0.000)
Year	0.530***	0.527***	0.524***	0.064***	0.064***	0.064***	-0.033***	-0.034***	-0.031***	0.002***	0.002***	0.002***
	(0.006)	(0.006)	(0.006)	(0.001)	(0.001)	(0.001)	(0.007)	(0.007)	(0.007)	(0.000)	(0.000)	(0.000)
_cons	-1055.145***	-1049.472***	-1045.690***	-128.252***	-127.602***	-127.160***	150.312***	150.801***	146.287***	-4.122***	-4.131***	-4.045***
	(12.655)	(12.690)	(12.680)	(1.780)	(1.782)	(1.780)	(13.173)	(13.215)	(13.203)	(0.114)	(0.116)	(0.115)
Topic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	140463	140463	140463	140463	140463	140463	140463	140463	140463	140463	140463	140463
R^2	0.286	0.286	0.286	0.347	0.347	0.347	0.171	0.170	0.171	0.096	0.090	0.093
Adj. R^2	0.286	0.286	0.286	0.347	0.347	0.347	0.171	0.170	0.171	0.096	0.090	0.093

Note: ***p<0.01, ** p<0.05, * p<0.1.

4.2.2. Comparison of the effects of different collaboration types on interdisciplinarity

To investigate whether inter-institutional collaboration research generates greater interdisciplinary knowledge integration than single-institution research, this section analyzes differential impacts of collaboration types on interdisciplinary knowledge integration. As illustrated in Fig. 5., the group labled "I" serves as the reference category, where coefficient magnitudes for other groups indicate their relative difference from this baseline.

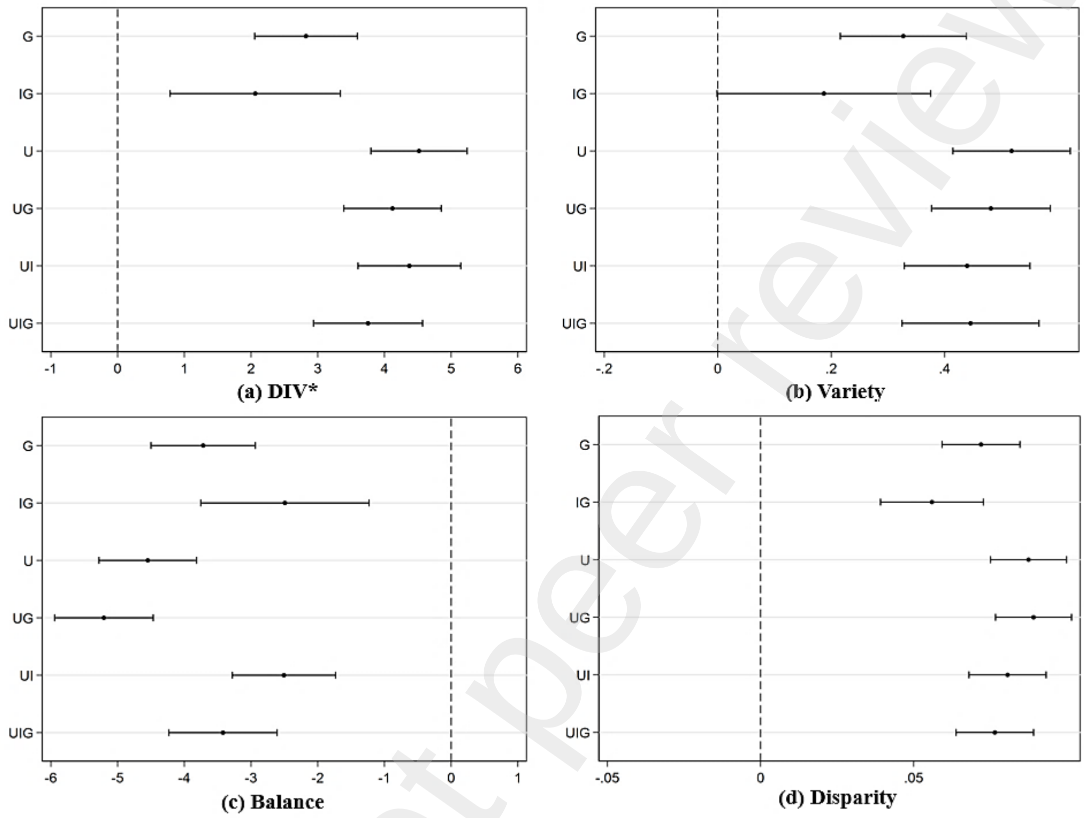

Fig. 5. Impacts of different collaboration types on interdisciplinarity.

Comparative analysis reveals that all inter-institutional collaboration types significantly enhance the degree of interdisciplinary knowledge integration, particularly when universities (U) are involved. As showed in Table 5 (Model 13), UG, UI, and UIG collaborations demonstrate 3.75 - 4.37point higher interdisciplinarity than industrial publications, representing 14.4%-16.8% of the mean value of DIV*, thereby confirming H2. The analysis about three distinct dimensions of interdisciplinary research reveals that inter-institutional collaborations enhance variety and disparity while reducing balance, confirming H2a and H2c but failing to validate H2b. This phenomenon may originate from institutional resource asymmetries. Universities, with diverse talent resources and heterogeneous disciplinary expertise, enable expanded knowledge coverage (variety) and integrate cognitively distant concepts (disparity) through collaboration. Conversely, collaborations excluding U tend to enhance balance by reducing disciplinary dominance, as the partners from I and G often prioritize specialized domain expertise.

Table 4
Comparison of different collaboration types.

Variables	(13) DIV*	(14) Variety	(15) Balance	(16) Disparity
G	2.824***	0.327***	-3.717***	0.072***
	(0.392)	(0.057)	(0.399)	(0.006)
U	4.518***	0.518***	-4.548***	0.088***

	(0.368)	(0.053)	(0.373)	(0.006)
IG	2.064***	0.187*	-2.492***	0.056***
	(0.651)	(0.096)	(0.643)	(0.009)
UG	4.121***	0.481***	-5.205***	0.089***
	(0.372)	(0.053)	(0.377)	(0.006)
UI	4.373***	0.440***	-2.506***	0.081***
	(0.393)	(0.057)	(0.394)	(0.006)
UIG	3.754***	0.446***	-3.420***	0.076***
	(0.417)	(0.062)	(0.414)	(0.006)
n_countries	0.354***	0.092***	-0.612***	-0.000
	(0.032)	(0.005)	(0.028)	(0.000)
n_authors	0.050***	0.018***	-0.333***	0.002***
	(0.011)	(0.002)	(0.010)	(0.000)
Pages	0.729***	0.135***	-0.356***	0.000***
	(0.006)	(0.001)	(0.005)	(0.000)
Doc_type	1.234***	0.278***	-1.064***	0.001***
	(0.018)	(0.003)	(0.014)	(0.000)
Year	0.535***	0.065***	-0.017***	0.002***
	(0.005)	(0.001)	(0.006)	(0.000)
_cons	-1069.809***	-129.362***	120.477***	-3.918***
	(10.777)	(1.538)	(11.182)	(0.093)
Topic	Yes	Yes	Yes	Yes
N	193205	193205	193205	193205
R^2	0.288	0.355	0.180	0.092
Adj. R^2	0.288	0.355	0.180	0.091

Note: ***p<0.01, ** p<0.05, * p<0.1.

4.2.3. Analysis of collaboration strategies of different research entities

The inherent heterogeneity among universities, industries and governments which manifested through divergent operational mandates, societal functions, governance structures, and innovation mechanisms, necessitates the selection of appropriate collaboration types. This section takes an actor-centric comparative analysis to identify the collaboration strategies. We evaluate different impacts of all possible collaborative types (single-institution U/I/G, bilateral UI/UG/IG, and trilateral UIG collaboration types) on the degree of interdisciplinary knowledge integration with each analysis respectively targeting U, I and G as primary beneficiaries. Specific performance advantages are quantified through fixed-effects regression modeling, yielding prescriptive guidance for optimizing institutional collaboration strategies. The regression analysis results are comprehensively detailed in Table 5.

Table 5
Collaborative strategies of different scientific research entities.

Entities	Variables	DIV*			Variety			Balance			Disparity		
		(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)
G	GI	-2.389***			-0.330***			2.950***			-0.039***		
		(0.543)			(0.081)			(0.530)			(0.006)		
	GU		0.242			0.050*			-1.738***			0.011***	
			(0.191)			(0.030)			(0.174)			(0.001)	
	GIU			0.058			-0.011			1.544***			-0.008***
				(0.202)			(0.032)			(0.183)			(0.001)
	Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Topic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	N	45804	45804	45804	45804	45804	45804	45804	45804	45804	45804	45804	45804
	Adj. R^2	0.294	0.293	0.293	0.377	0.377	0.377	0.179	0.181	0.180	0.052	0.051	0.049
I	IG	-2.148***			-0.248***			0.559			-0.026***		
		(0.553)			(0.083)			(0.542)			(0.006)		
	IU		1.013***			0.089**			1.256***			0.003*	
			(0.246)			(0.036)			(0.230)			(0.002)	
	IGU			-0.643**			-0.043			-1.528***			0.002
				(0.258)			(0.038)			(0.240)			(0.002)
	Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Topic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	N	11534	11534	11534	11534	11534	11534	11534	11534	11534	11534	11534	11534
	Adj. R^2	0.310	0.311	0.310	0.383	0.383	0.383	0.183	0.185	0.186	0.086	0.083	0.083
U	UG	-0.081			0.040**			-2.391***			0.011***		
		(0.128)			(0.019)			(0.118)			(0.001)		
	UI		0.137			-0.053**			2.717***			-0.012***	
			(0.153)			(0.022)			(0.143)			(0.001)	
	UIG			-0.032			-0.009			1.218***			-0.007***
				(0.201)			(0.032)			(0.182)			(0.001)
	Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Topic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	N	52260	52260	52260	52260	52260	52260	52260	52260	52260	52260	52260	52260
	Adj. R^2	0.295	0.295	0.295	0.374	0.374	0.374	0.186	0.186	0.180	0.063	0.062	0.060

Note: ***p<0.01, ** p<0.05, * p<0.1.

When governments participate in industrial scientific research (IG), regression analyses reveal statistically significant negative impacts on interdisciplinarity (coefficient = -2.389, $p<0.01$), variety (coefficient = -0.330, $p<0.01$), and cognitive disparity (coefficient = -0.039, $p<0.01$). Conversely, collaborations with universities (UG or UIG) demonstrate positive impacts. This finding, coupled with descriptive evidence that IG publications account for only 3.2% of total publications, suggests that industry's profit-driven motives sometimes might conflict with the government's public interest objectives, impeding the development of mechanisms for sustainable convergence of interests. For example, climate adaptation research typically requires long-term public investment, which is inconsistent with industry's short-term return on investment framework. Thus, prioritizing partnerships over universities currently represents the optimal strategy for governments seeking interdisciplinary advancement.

For industry, collaborating with U (UI) yield substantial interdisciplinary enhancement, with interdisciplinarity increasing by 1.013 standard deviations (SD) ($p<0.001$), balance improving by 1.256 SD ($p<0.01$), and slight improvement in variety (0.089 SD) and disparity (0.003 SD). However, governmental involvement introduces significant negative effects (IG: coefficient = -2.148, $p<0.01$, IGU: coefficient = -0.643, $p<0.05$). This phenomenon reflects industry's recognition of universities as important innovation catalysts. Academic partnerships provide access to specialized human capital, commercial technologies, and frontier knowledge that enable market diversification beyond core competencies. For example, energy firms collaborating with the researchers in material science can develop novel carbon capture solutions while expanding into adjacent sustainable technology markets. This symbiotic relationship transforms universities into innovation incubators that reduce industrial R&D risks.

Universities demonstrate a stable capacity for integrating interdisciplinary knowledge. The collaborations with G or I neither significantly enhance nor diminish interdisciplinarity. This institutional autonomy stems from academia's unique capacity as knowledge repositories, with multidisciplinary talent pools and diverse methodologies enabling self-sufficient interdisciplinary knowledge integration. Different collaboration patterns have slightly different effects on the three sub-divided dimensions of interdisciplinarity. Collaborations involving G has enhanced variety (0.040 SD, $p<0.05$) and disparity (0.011 SD, $p<0.01$), likely due to policy-driven research agenda broadening. Trilateral UIG collaborations significantly improve balance (1.218 SD, $p<0.01$) by integrating complementary resources. This positions universities as indispensable network orchestrators, utilizing their capability of "knowledge sponge" to absorb and recombine diverse inputs without harming the interests of other stakeholders.

4.3. Robustness check

To verify the robustness of these findings, a series of checks were performed through variable supplementation and temporal sample refinement. First, to address potential omitted variable bias, we introduced a binary covariate (1 = present, 0 = absent) of institutional participation in climate change research, which has ever been identified as an important factor affecting the interdisciplinary knowledge integration (Zuo & Zhao, 2018). Variance inflation factor (VIF) analysis confirmed the absence of multicollinearity (VIF < 5), while significance testing established its relationship with the dependent variables. All models exhibited enhanced explanatory power, as evidenced by improved R^2 values, confirming the robustness of the results. Second, temporal robustness was assessed by restricting the analytical sample to publications from 2017 to 2021 (n = 100,253) with 2017 as the reference baseline. The results remained consistent with the original regression model, that is, compared to independent publications by I and G, publications from U showed higher DIV*, variety and disparity, but the balance of I remained relatively higher than U and G.

6. Discussion and conclusion

In an environment of intensifying global competition, strategically coordinating multi-stakeholder innovation strategies constitutes critical pathways for advancing scientific development. Weakening traditional disciplinary barriers and promoting the integration of interdisciplinary knowledge would empower sustainable momentum for scientific frontiers. This study constructs tripartite triple helix networks composed of U, I and G of climate change research. By empirical analysis of collaborative types and their differential impacts on interdisciplinary knowledge integration, this study elucidates the following findings.

Universities, industries, and governments exhibit distinct functions in advancing interdisciplinary knowledge integration. The results of descriptive analysis reveals that U dominate climate change research, producing 66.93% publications (82.6 times I and 13.5 times G publications), which might attributed to the strategic knowledge resources that universities possess diverse disciplines. UG collaborations exhibit the strongest growth (14.7% annually), contrasting with underdeveloped IG collaborations. This phenomenon reveals the neglection IG interactions, suggesting institutional logics impede inter-institutional resources convergence. These findings are consistent with the conclusions of the existing research (Liu & Zhu, 2023). To leverage universities capacity for interdisciplinary knowledge integration, interdisciplinary research platforms, research centers, consolidated laboratories and joint appointments could be establish to integrate academic resources. For example, Global Alliance of Universities on Climate (GAUC) has enhanced innovation outputs and high-quality patents (Yu et al., 2025). It is suggested that governments should provide targeted investment in such entities through national research funding mechanisms while creating specialized career pathways for interdisciplinary scholars. This synergistic approach operationalizes the Triple Helix theory by transforming capacity of U into dynamic innovation catalyst that generate interdisciplinary research through enhancing innovation translation, optimizing talent cultivation programs, and recombining knowledge ecosystems.

Different collaboration models have varying effects on the integration of interdisciplinary knowledge. UG collaborations demonstrate the most accelerated growth trend, while IG collaborations remain underdeveloped, indicating persistent translational gaps between regulatory frameworks and market solutions. Although UI collaborations significantly strengthen diversity of climate change research, the incorporation of governmental participants reduces interdisciplinary knowledge integration. This phenomenon confirms the nonlinear institutional dynamic mechanism proposed by Etzkowitz and Leydesdorff (1995). In addition, the recent network of UIG collaboration further reveals a structural transition toward small-world characteristics, evidenced by increasing clustering coefficients and decreasing path lengths. This evolution signifies progressing integration between entity clusters and distant knowledge. Compared to other collaboration types, UIG collaboration is more conducive to promoting the integration of interdisciplinary knowledge. This quantitative analysis empirically validates the Ursić et al.'s (2022) qualitative conclusion, that traditional higher education institutions focused on single-discipline approaches lacks interdisciplinarity. Nevertheless, trilateral UIG collaborations remain substantially underexploited despite their exponential growth, representing critical potential is still far from being fully realized.

This study explores institutional collaboration strategies that may support interdisciplinary knowledge integration. The findings suggest that universities play a central role, likely due to their structural pluralism and capacity to engage with diverse disciplinary perspectives.Collaboration between universities and industry (UI)appears particularly effective, potentially reflecting the role of technology transfer in linking theoretical and applied domains. By contrast, collaborations involving government show comparatively lower levels of interdisciplinarity, which may be associated with differences in institutional priorities and accountability structures. These results point to several cautious policy implications. Universities could serve as key coordinators in facilitating interdisciplinary resource integration. Industry may benefit from closer embedding within academic ecosystems to strengthen connections between research and application. Governments, rather than primarily acting as regulators, could further support interdisciplinary collaboration through enabling and incentive-based approaches, such as targeted funding mechanisms for cross-sector integration (Lebeau, 2008).

7. Limitations

This study has two limitations. First, although we applied a rigorous discrimination procedure to identify institution attribution, including semantic standardization through text similarity algorithms followed by manual verification, some ambiguity remains, particularly for abbreviated entities and non-standardized names. These inconsistencies affect approximately 3.93% of institutional records and could be further reduced by incorporating more comprehensive term dictionaries (Choi et al., 2015). Second, while this study identifies significant correlations between collaboration types and interdisciplinary knowledge integration, it does not investigate whether such collaboration-driven interdisciplinarity translates into greater academic, societal, or policy impact. Future research will address this gap by incorporating multidimensional impact indicators, including citation networks (academic impact), policy documents, and Altmetric measures (societal engagement) (Paswan, 2022). This extension may offer more comprehensive evidence to inform the design of innovation ecosystems that support effective interdisciplinary knowledge integration.

CRediT authorship contribution statement

Wenjing Xiong: Writing − original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Software, Project administration, Methodology, Funding acquisition, Formal analysis. **Yijia Song:** Software, Data curation, Methodology. **Hui-zhen Fu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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