



REVIEW



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Insight into border carbon adjustment: a visual bibliometric analysis from 2009 to 2024

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Over the past 15 years, research on Border Carbon Adjustment (BCA) advanced rapidly. However, comprehensive reviews of this field remained scarce, let alone visual analyses. Based on bibliometrics, this paper utilized CiteSpace and VOSviewer to analyze BCA-related literature from the WOSCC, CNKI, and arXiv databases spanning 2009 to 2024. The findings reveal three key insights: (1) Using WOSCC data, we construct the first knowledge network encompassing 46 countries, 464 institutions, 712 authors, and 122 journals. Through keyword timeline analysis, we trace the policy-driven thematic evolution of BCA research, while literature co-citation clustering identifies five global research hotspots: BCA mechanism design, policy efficacy assessment, socioeconomic impacts, supply chain complexities, and post-implementation governance strategies. (2) CNKI-based analysis highlights China's transition from passive policy evaluation to proactive institutional innovation, offering a replicable framework for emerging economies. Meanwhile, arXiv publications emphasize technological innovations in emission reduction. (3) Emerging research frontiers coalesce around five directions: Multilateral rule games & North-South coordination, BCA policy refinement, Climate justice frameworks, AI/blockchain-driven carbon pricing and hybrid technology innovation, and advances in quantitative analytical tools. Furthermore, emerging economies are seeking context-specific solutions, such as China's approach of integrating digital finance into the pathways toward achieving the dual-carbon goals.

Introduction

As an international climate governance agreement adopted at the United Nations Climate Conference, the core goal of the Paris Agreement is to limit the increase in global average temperature to within 2 degrees Celsius above pre-industrial levels (Mitchell et al., 2018; Rogelj et al., 2016). However, its implementation faces many challenges, one of which is the carbon leakage caused by differences in emission reduction goals and policy stringency (Babiker, 2005; King and van den Bergh, 2021). Carbon leakage refers to the phenomenon that when a country unilaterally implements a carbon pricing policy, its positive impact on the global environment is weakened, and the spillover effect in the international market results in an increase in carbon emissions in other countries, which partially or completely offsetting the effectiveness of the country's emission reduction (Branger and Quirion, 2014a; Michalek and Schwarze, 2015). In order to deal with the carbon leakage problem, current strategies include

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strengthening international cooperation, output-based emission allowance allocation mechanism, and Border Carbon Adjustment (BCA) (van Asselt and Brewer, 2010). Among them, many scholars have pointed out that BCA is a very effective method (Christoph Böhringer et al., 2012a, 2012b; Mörsdorf, 2022; Winchester et al., 2011), as it represents a climate governance mechanism specifically designed to mitigate carbon leakage risks and preserve the integrity of domestic carbon pricing systems. This mechanism achieves competitive equity by levying carbon cost differentials on imports equivalent to domestic producers' compliance costs, while simultaneously allowing export rebates for industries subject to carbon pricing regulations (Mehling et al., 2019). The call to introduce BCA originally originated in industrialized countries, but this concept remained at the level of theoretical discussion (Cosbey et al., 2019; DrÖge et al., 2004). Until 2023, the European Union formally legislated to establish the Carbon Border Adjustment Mechanism (CBAM), which sparked a new wave of discussion (Bellora and Fontagné, 2023; Leal-Arcas et al., 2022). In this context, a systematic review of the literature in the field of BCA and in-depth insight into current research hotspots and cutting-edge developments is of great significance for guiding scholars to explore research in this field.

Currently, there are five major reviews in the field of BCA. Ma and Xu (2024) systematically reviewed the potential economic impact of BCA on target countries based on 109 articles, pointing out that major energy-exporting and industrialized countries will be adversely affected. The degree of influence for carbon-intensive exporting countries and countries with higher economic risks mainly depends on factors such as the identity of the implementing country and the specific design of the BCA. Zhong and Pei (2024) conducted a literature review of CBAM's latest economic research, highlighting the potential impact of CBAM in protecting fair competition; reducing carbon leakage; and limiting global welfare costs. Böhringer et al. (2022) reviewed the potential environmental and economic impact of BCA in reducing carbon leakage, restoring competitiveness, cost effectiveness, fairness, and strengthening cooperation, noting that the feasibility of the BCA program may be significantly reduced due to current legal and practical implementation restrictions. Overland and Huda (2022) aimed to study the connection between CBAM and climate clubs. Fournier Gabela et al. (2024) proposed an agriculture-based CBAM design. However, existing reviews are mainly limited to a specific aspect of BCA, such as the policy impact level. No scholar has conducted a comprehensive review of the research course of BCA, let alone systematically summarize and analyze research in this field through information visualization. Therefore, this study integrates literature from the WOSCC, CNKI, and arXiv databases, employing CiteSpace and VOSviewer to comprehensively analyze knowledge networks, research hotspots, and frontiers in the field through bibliometric visualization.

We will answer the following questions about BCA:

RQ1: What are the pivotal countries/regions, institutions, authors, and journals in BCA research, and how do their collaboration networks operate globally?

RQ2: What are the dominant research hotspots and thematic evolution trends in BCA studies

RQ3: What are the research frontiers in BCA studies?

The remainder of this paper is structured as follows: "Methodology" describes the research instruments, methodologies, and data sources. "Results and discussion" analyzes and discusses the literature research from different databases, identifying the research frontiers in this domain. "Conclusions and limitations" provides a synthesis of the findings and addresses the limitations.

Methodology

Data collection. This study selects Web of Science Core Collection (WOSCC) as the primary database due to its extensive indexing of multidisciplinary, high-impact, international journals and its high compatibility with Citespace software (Archambault et al., 2006; Singh et al., 2021). To ensure comprehensive coverage, we incorporate data from China National Knowledge Infrastructure (CNKI), given China's significant role as the world's largest developing country and a major supplier of carbon-intensive products to the EU¹ (S. Yan et al., 2023). Additionally, we include arXiv preprint data to capture the latest BCA research trends, enhancing the objectivity and timeliness of our analysis through multi-source cross-validation.

We downloaded relevant publications from WOSCC on 2024.11.9, applying the PRISMA 2020 guidelines with the following search strategy: TS = ("border carbon adjustment*" OR "carbon border adjustment*" OR "carbon border adjustment mechanism*" OR "carbon border adjustment measure*" OR "carbon border tax adjustment*" OR "border carbon tax adjustment*" OR "carbon border tax*" OR "border carbon tax*" OR "carbon tariff*"). Citation indexes were limited to SCIE and SSCI (Hue and Hung, 2025). Language was restricted to English. The study period ranged from 2009.1.1 to 2024.11.8. Research directions were filtered to exclude low-yield disciplines (e.g., physical geography, mathematical methods in social sciences), where each contributed ≤ 3 articles irrelevant to BCA research. Document types were confined to articles and review articles (Tang et al., 2024). A total of 300 articles were finalized for subsequent visual analysis, with the data collection process illustrated in Fig. 1.

The CNKI database employed the same search terms, selecting academic journals with source categories restricted to PKU Core Journals and CSSCI to ensure correspondence with high-quality articles from WOSCC. The study period was from 2009.1.1 to 2024.11.8. A total of 499 articles were retrieved, downloaded, and exported on 2025.4.4 for subsequent visualization analysis. The data collection process is illustrated in Fig. 1.

The preprint repository arXiv employed the same search terms on 2025.4.10, with the study period from 2009.1.1 to 2024.11.8. Using an "All fields" query, a total of 11 articles were retrieved. Compared with WOSCC, 4 duplicate articles were removed, leaving 7 articles for subsequent analysis. The data collection process is illustrated in Fig. 1.

Bibliometric analysis and visualization software. Bibliometric analysis is a method that uses software to visualize the distribution, connections among, and trends of countries, institutions, authors, journals, and research areas (Ellegaard and Wallin, 2015). It provides valuable predictions for future development in specific areas by providing insights into hot spots and trends (Chen, 2006). As databases such as the WOSCC become increasingly accessible to research data, bibliometric analysis is becoming increasingly popular as a research framework for assessing impact and evidence (Donthu et al., 2021; Wang et al., 2024).

This paper uses the built-in functions of the WOSCC to obtain key indicators such as the number of publications, citation frequency, and h-index (Joshi, 2014). In particular, the h-index, as a quantitative measure, was originally used to evaluate the contribution of individual researchers to academia (Bornmann and Daniel, 2007). Gradually, the application scope of the h-index has expanded to evaluate the academic influence of national or regional research teams, research institutions, academic groups, and even academic journals (Bornmann and Daniel, 2009). In addition, we use the Impact Factor (IF) and the latest version of

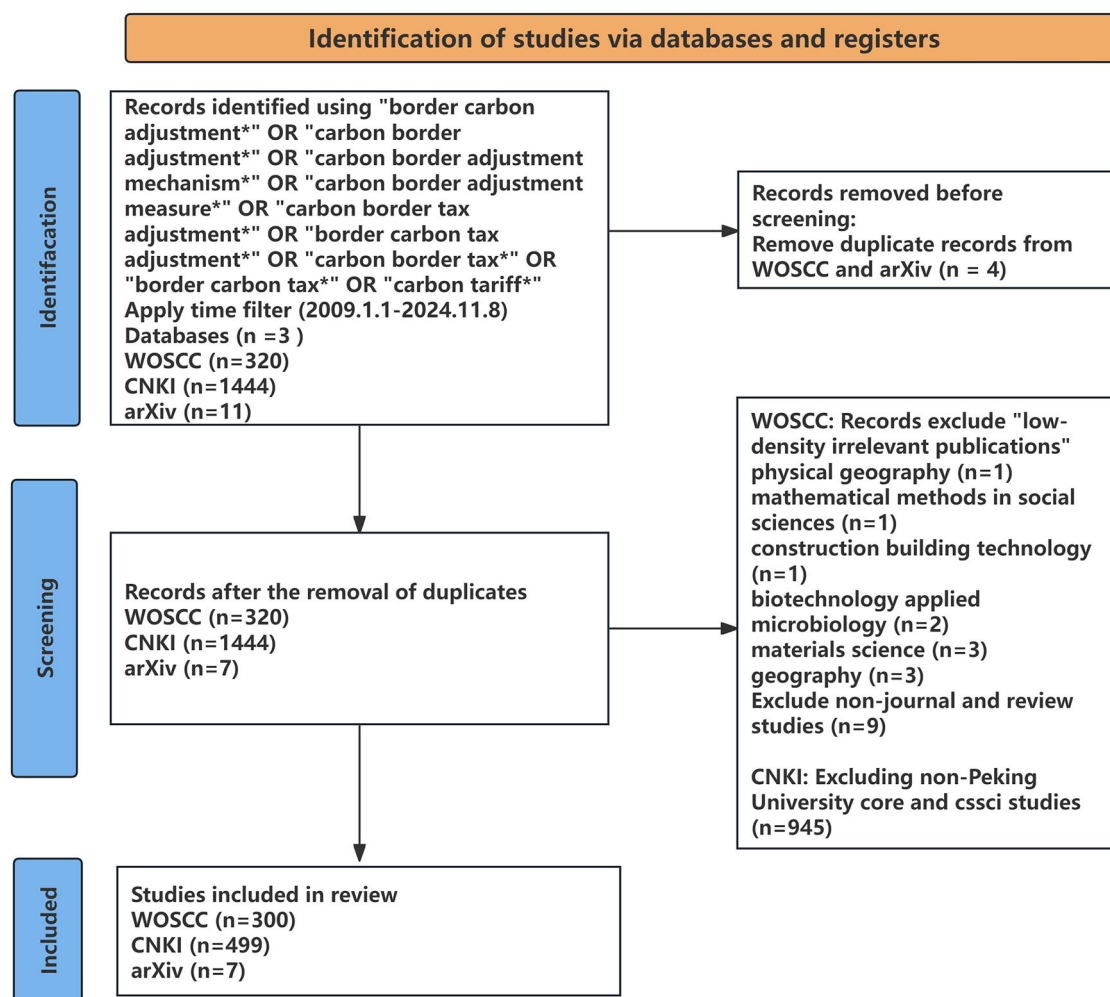


Fig. 1 Flowchart of literature screening using PRISMA2020 for WOSCC, CNKI, and arXiv.

Journal Citation Reports (JCR) as key indicators to measure the scientific value of journals (Eyre-Walker and Stoletzki, 2013; Magri and Solari, 1996).

In order to visualize and build a bibliometric network, this paper uses VOSviewer (version 1.6.20) and CiteSpace (version 6.4.R1) for bibliometric analysis (Moral-Muñoz et al., 2020; Todeschini, 2016). "VOSviewer, developed by Leiden University in the Netherlands, facilitates in-depth analysis of citation networks, co-citations, keyword co-occurrence, and international cooperation (van Eck and Waltman, 2017). Because it can simultaneously draw a network diagram and detect clusters in the network, the software can be combined with cluster analysis methods to divide the network into different clusters (Arruda et al., 2022). The CiteSpace software, created by Professor Chen Chaomei, is based on the Java platform to detect and identify the emergence and development of new technologies (Chen, 2014). CiteSpace can quickly understand the latest developments in literature, locate relevant information, such as core research literature, authors, etc., and draw a chronological chart of citations based on the relationship between literature development and the evolution of the field (Chen, 2017).

Results and discussion

Annual publication volume and trend. Between 2009 and 2024, we collected 300 and 499 articles related to BCAs from the WOSCC database and the CNKI database, respectively. Figure 2 illustrates the annual publication trends in both databases. For

WOSCC, the initial publication count stood at 2 articles in 2009, rising to 17 by 2012 as the EU Aviation Carbon Tax dispute prompted academic discussion on carbon tariff legitimacy (Mendes and Santos, 2008). The 2015 Paris Agreement stimulated research on carbon leakage, with a rebound in related articles to 13 in 2016 (Christoff, 2016). However, the U.S. withdrawal from the Paris Agreement in 2017 resulted in a decline in publications from 2017 to 2019 (Pickering et al., 2018). Subsequently, the EU's CBAM proposal in the 2019 European Green Deal reignited BCA research (Siddi, 2020). For CNKI, China's initial carbon intensity pledge at the 2011 Copenhagen Conference (COP15) (Christoff, 2010) and emphasis on low-carbon economic development in domestic policies² sparked academic interest (average of 88 articles per year in 2010–2011). The establishment of China's carbon market in 2013 partially diverted research attention, leading to a subsequent decline in publications (Jiang, 2014). Until 2019, the EU CBAM proposal prompted a recovery in BCA-related publications, albeit not reaching previous peaks. A comparative analysis reveals that academic research is closely linked to policy, with WOSCC reflecting global policy trends and CNKI potentially emphasizing Chinese policy responses.

Analysis based on WOSCC database

Important countries or regions and cooperation network. BCA research has garnered global attention and is currently being conducted in 46 countries or regions worldwide. Table 1 lists the

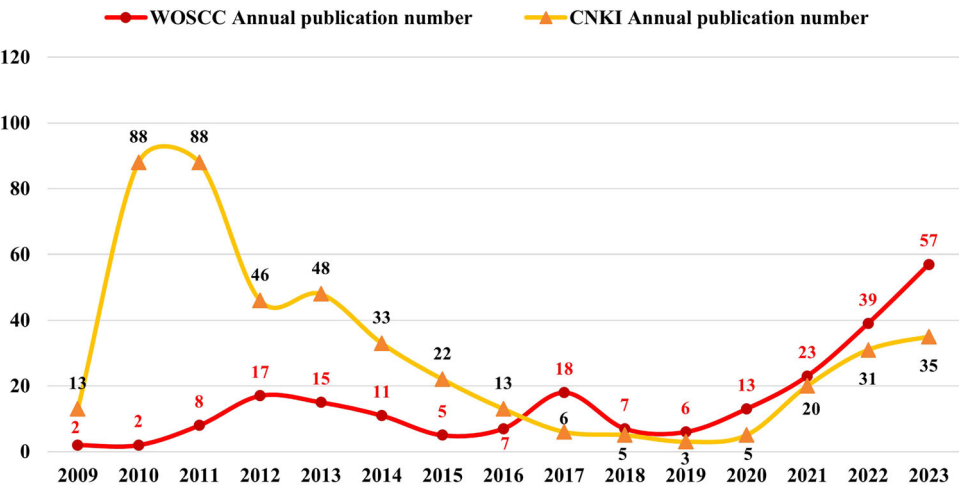


Fig. 2 A comparison of annual publication volumes based on WOSCC and CNKI.

Table 1 Top 10 countries/regions with the most published.					
Rank	Country/region	Counts	Citations	Average citations	H-index
1	China	90	939	10	17
2	United States	67	1864	28	24
3	Germany	54	1683	31	23
4	United Kingdom	38	884	23	13
5	France	20	487	24	11
6	Norway	18	765	43	12
7	Canada	11	362	33	6
8	South Korea	11	60	5	4
9	Australia	10	346	35	6
10	Italy	10	257	26	6

top 10 countries/regions in terms of the number of publications, along with information such as total citations, average citations, and h-index. China leads with an absolute advantage, publishing 90 articles (30%), followed by the United States with 67 (22.33%), and Germany with 54 (18%). Together, these three countries account for 70.33% of the total publications, serving as the main contributors and leaders in this field. In terms of citations, the United States ranks first with 1864 total citations, Germany second with 1683, and China third with 939. Notably, despite China's high ranking in total citations among the top ten, its average citations are significantly lower, at only 10, compared to Germany's 31 and the United States' 28. Additionally, Norway has the highest average citations, with 43. In terms of the h-index, China, the United States, and Germany have values of 17, 24, and 23, respectively, which are notably higher than those of other countries, reflecting their higher academic standards.

Figure 3 presents a national geographical visualization cooperation network map generated by VOSviewer, which screens the top 30 countries in terms of BCA publications with a minimum of two articles. The network is divided into seven clusters, each represented by a distinct color. The size of the nodes indicates the number of publications, while the connections between them symbolize cooperation (Van Eck and Waltman, 2011). It is evident that key countries in the BCA field are primarily located in Europe, North America, and Asia. In Europe, Germany, Norway, and Spain stand out with significant network nodes, aligning with the EU's position as an early international organization promoting climate policy and reflecting the advanced exploration of European countries in mitigating climate

change (Oberthür and Roche Kelly, 2008). In addition, the United States and China also demonstrate robust research strength and influence (Bao et al., 2013). The dense and intertwined connections between these three countries—the US, China, and Germany—not only reveal their core roles in the global BCA network but also showcase their crucial function as bridges connecting different continents and fostering transnational cooperation (Kuehner et al., 2022).

Key institutions and collaborative network. Through the analysis of 464 research institutions, important institutions and cooperation networks for BCA research can be identified. Table 2 details the top ten research institutions in productivity and their information. Carl Von Ossietzky Universität Oldenburg leads with 16 publications (5.33%), followed by the University of London with 8 (2.67%). Beijing Institute of Technology, Tsinghua University, and the University of Wisconsin System tie at 7 (2.33% each). In citations, Carl Von Ossietzky Universität Oldenburg (906 citations, avg. 57 per paper) and the University of Wisconsin System (507 citations, avg. 72 per paper) significantly outperform others. Statistics Norway ranks third (231 citations, avg. 46 per paper). Notably, Carl Von Ossietzky Universität Oldenburg also boasts the highest h-index of 14, affirming its leading role in BCA research.

Figure 4 showcases an institutional cooperation network in the field of BCA produced by CiteSpace. In this network, nodes represent institutions, filtered using the g-index method with a threshold K set at 100 to include a broader range of institutions. The research spans from 2009 to 2024, employing an annual slicing approach (Chen, 2014). The display strategy for node labels is to showcase only those institutions with more than 4 publications. The size of the nodes reflects the number of publications, while the color represents the publication timeline. The density of connecting lines indicates the intensity of cooperation (Wang and Lu, 2020). Early institutions that were deeply involved in this field, such as Carl Von Ossietzky Universität Oldenburg, Statistics Norway, Norwegian University of Life Sciences, and University of Wisconsin System, have laid a solid foundation for the initial construction of a theoretical framework, but activities have slowed down in recent years (Christoph Böhringer et al., 2012a, 2012b; Böhringer et al., 2016; Böhringer et al., 2014). Although the cooperation networks of Beijing Institute of Technology, Xiamen University, Tsinghua University, Australian National University are relatively sparse, they have all shown a high degree of activity in the current field,

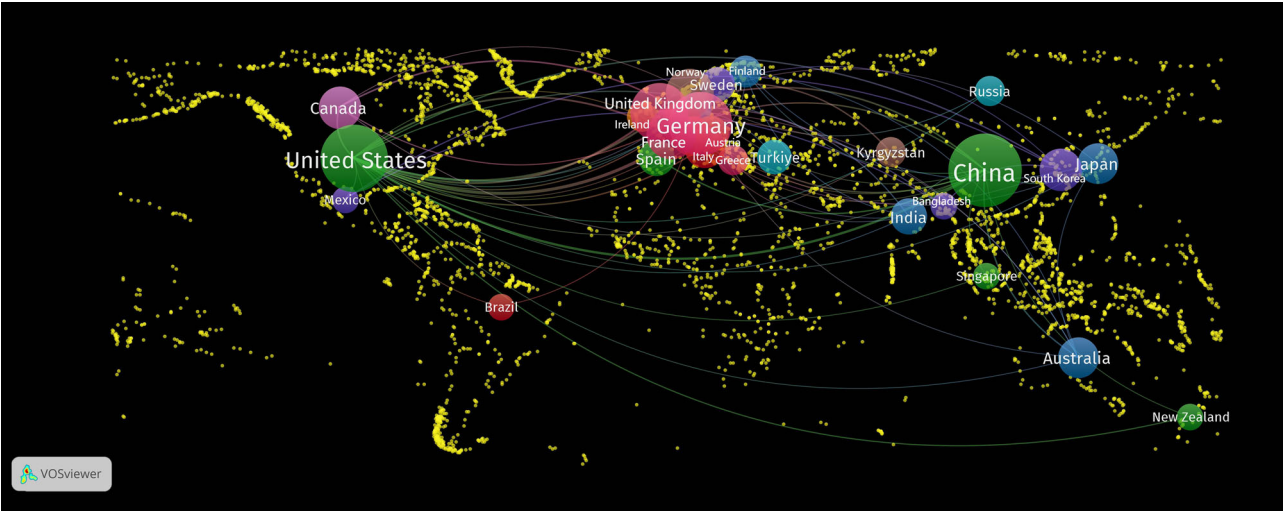


Fig. 3 Country/Region collaboration network analysis based on the WOSCC database.

Table 2 Top 10 institutions that publish the most articles.						
Rank	Institution	Country	Counts	Citations	Average citations	H-index
1	Carl Von Ossietzky Universität Oldenburg	Germany	16	906	57	14
2	University of London	United Kingdom	8	145	18	6
3	Beijing Institute of Technology	China	7	106	15	4
4	Massachusetts Institute of Technology	United States	7	221	32	6
5	Tsinghua University	China	7	60	9	5
6	University of Wisconsin System	United States	7	507	72	6
7	University of Oxford	United Kingdom	6	141	24	6
8	Australian National University	Australia	5	66	13	3
9	Chinese Academy of Sciences	China	5	122	24	3
10	Statistics Norway	Norway	5	231	46	4

reflecting their exploration of the frontiers of the field (Ren et al., 2023; Siy et al., 2023; Sun et al., 2024).

An important network of authors and collaborators. Through an analysis of 712 authors and 6462 co-cited authors, significant authors and collaborations in this field have been identified. Table 3 lists the top ten authors by publication volume and the top ten co-cited authors by citation count. Boehringer tops the list with 12 papers, closely followed by Jakob with 7. Tied in third place with five papers each are Overland, Rutherford, Fischer, and Rosendahl. Notably, despite similar publication volumes among these top authors, there are significant differences in citation counts. Boehringer leads with 766 citations, while Jakob and Overland have relatively lower totals of 123 and 64 citations, respectively. Rutherford and Fischer also stand out in terms of citations, with 542 and 482, respectively, demonstrating strong influence. In terms of average citations per paper, Rutherford ranks first with 108, followed by Fischer with 96 and Boehringer with 64. These three authors excel both in output and academic influence within the BCA field.

Figure 5 is a co-cited author chord diagram generated by VOSviewer in conjunction with the Charticulator website. It displays the co-occurrence among 26 highly cited authors, each cited over 40 times. The entire circle is divided proportionally based on the citation frequency of each author. The wider the chord segment, the stronger the co-citation relationship between the authors it represents. Boehringer, Fischer, and Branger rank among the top three in terms of citations, with 407, 117, and 103 citations, respectively. Furthermore, authors such as Boehringer, Babiker, Fischer, Hoel, Kuik, Monjon, Nordhaus, and others have

demonstrated close co-citation relationships, revealing their high correlation and mutual influence within academic research and knowledge contexts.

Important journals and subject trends. A total of 122 academic journals have published articles in the BCA field, with the top ten in publication volume and citation listed in Table 4. The top ten journals account for 38.67% of total publications, six of which are also in the top ten most cited. “Climate Policy” published the most articles (23), with 486 citations. “Energy Economics” followed with 22 articles, but had a higher total of 843 citations. “Energy Policy” published 19 articles, with a total of 565 citations. These three are high-quality Q1 journals in the JCR, with IFs of 5.3, 13.6, and 9.3, respectively.

This study generates, for the first time, a dual-map overlay of BCA journal research (Fig. 6). The left half shows the discipline distribution of the citing journals (in dark yellow), representing the research frontier. The right half displays the discipline distribution of the cited journals (in light blue), reflecting the knowledge base (Chen, 2006). The numbers in parentheses next to the journal names indicate publication volumes (on the left) and citation counts (on the right). The colors of the arcs match those of the citing journals, and the ellipses represent journal clusters, with the number of ellipses reflecting the quantity of journals within each cluster (Chen, 2014).

Based on Fig. 6, we observe two clusters of citing journals on the left. The top-left cluster (in bright yellow font) includes [10] Journal of Cleaner Production, categorized under “Veterinary, Animal, Science.” The bottom-left cluster (in dark blue) comprises [19] Energy Policy, [22] Energy Economics, and [23]

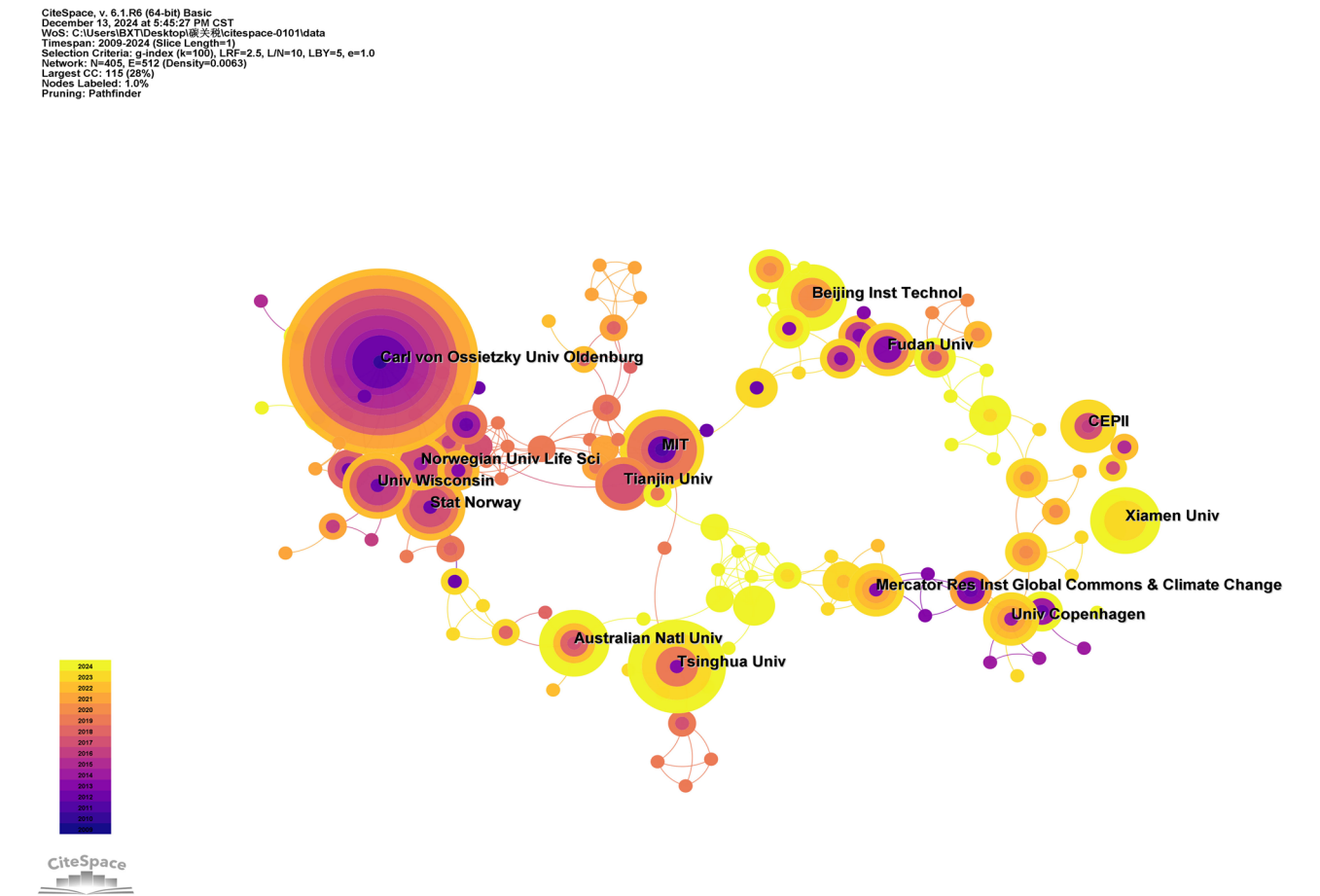


Table 3 Top 10 high-yield authors and co-cited authors.							
Rank	Author	Counts	Citations	Average citations	H-index	Co-cited author	Citations
1	Boehringer, C	12	766	64	10	Boehringer, C	407
2	Jakob, M	7	123	18	5	Fischer, C	117
3	Overland, I	5	64	13	4	Branger, F	103
4	Rutherford, T. F.	5	542	108	5	Peters, GP	92
5	Fischer, C	5	482	96	5	Babiker, MH	84
6	Rosendahl, K	5	316	63	5	Monjon, S	83
7	Leonelli, GC	4	26	7	3	Kuik, O	82
8	Winchester, N	4	95	24	4	Cosbey, A	80
9	Lin, BQ	4	22	6	2	Nordhaus, W	71
10	Zhang, ZX	4	111	28	4	Jakob, M	70

Climate Policy, all focusing on “Economics, Economic, Political”. This indicates that these disciplines are at the forefront of BCA research, reflecting in-depth exploration of energy policies and climate change from economic, political, and scientific perspectives. On the right, the cited journal cluster (in dark blue) including [725] Energy Policy and [697] Energy Economics, among others, predominantly focuses on “Economics, Economic, Political,” demonstrating that these disciplines are not only at the cutting edge of BCA research but also serve as the foundational disciplines supporting the study. A smaller subset, [147] Applied Energy and [247] Journal of Cleaner Production, focuses on “Environmental, Toxicology, Nutrition,” highlighting that these disciplines provide indispensable knowledge support for BCA research and showcasing the unique appeal of interdisciplinary integration in BCA research.

Keywords time line analysis. This paper is based on a complementary analysis using both VOSviewer (Van Eck and Waltman, 2011) and CiteSpace (Chen, 2006) software to construct a co-occurrence network with 1113 keywords. The screening criteria were set as a co-occurrence frequency of no less than 7 for the analysis conducted using VOSviewer (as depicted in Fig. 7) or no less than 10 for the analysis conducted using CiteSpace (as shown in Fig. 8). The node size reflects the keyword frequency, and the colors and lines correspond to a year color scale. Since BCA is a policy instrument and inextricably linked to national regulations, the keyword timeline is analyzed in conjunction with policies.

- (1) Initial Exploration Period (2009–2017)
- 2009: Global Origins of BCA Policy Initiatives

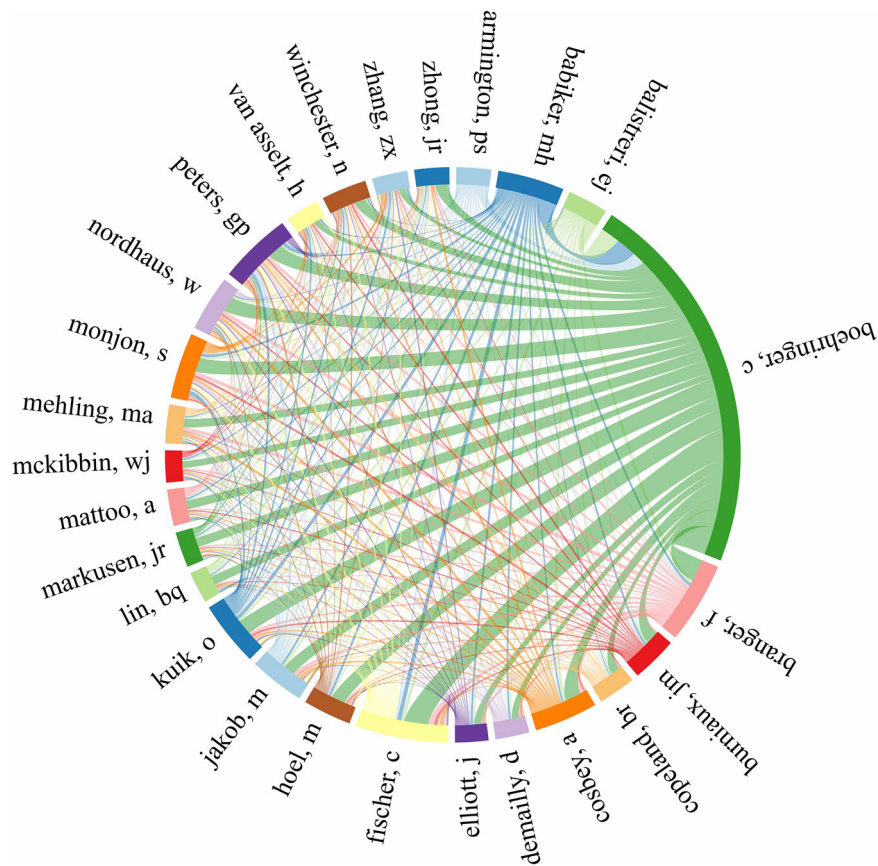


Fig. 5 Chord diagram of co-cited authors based on WOSCC database.

Table 4 Top 10 journals and co-cited journals.								
Rank	Journal	Counts	Citations	H- index	JCR	IF(2023)	Co-cited Journal	Citations
1	Climate Policy	23	486	11	Q1	5.3	Energy Policy	725
2	Energy Economics	22	843	15	Q1	13.6	Energy Economics	697
3	Energy Policy	19	565	15	Q1	9.3	Climate Policy	378
4	Sustainability	11	64	5	Q2	3.3	Journal of Environmental Economics and Management	325
5	Journal of Cleaner Production	10	189	7	Q1	9.8	Ecological Economics	316
6	Environmental and Resource Economics	8	144	5	Q1	3.2	Journal of Cleaner Production	247
7	Energies	7	79	4	Q3	3	American Economic Review	235
8	World Trade Review	6	20	2	Q1	2.2	Journal of International Economics	224
9	Applied Energy	5	136	4	Q1	10.1	Environmental and Resource Economics	209
10	Ecological Economics	5	230	5	Q1	6.6	Nature Climate Change	153

The European Union adopted the Revised Emissions Trading System Directive, introducing the Carbon Leakage List during Phase III of the EU ETS (2013–2020)³. This mechanism provided free quota allocations to high-carbon industries facing international competition, sparking academic research on the connection between “competitiveness loss” and “border tax adjustment” (Veel, 2009). The U.S. House of Representatives passed the American Clean Energy and Security Act, which proposed International Reserve Allowances on imported goods⁴. Although never enacted, this was the first domestic bill to explicitly include BCA provisions, fueling discussions on “trade” (Weber and Peters, 2009) and “border tax adjustment” in academic circles (Izard et al., 2010; Zhang, 2010).

The Copenhagen Climate Summit (COP15) recognized “border measures to address competitiveness”⁵. elevating BCA from unilateral national actions to a multilateral climate governance agenda. It also causes more and more international scholars to join the research of BCA (Gros and Egenhofer, 2011; Holmes et al., 2011; Moore, 2011). 2012: EU ETS Phase III Launch The launch of Phase III of the EU ETS (2013–2020) marked the inclusion of the aviation sector in carbon regulations and a gradual increase in the auction quota ratio from 20 to 70% [3]. These reforms highlighted terms like “unilateral climate policy”, “energy”, and “EU ETS” in academic discourse (Helm et al., 2012; Springmann, 2012).

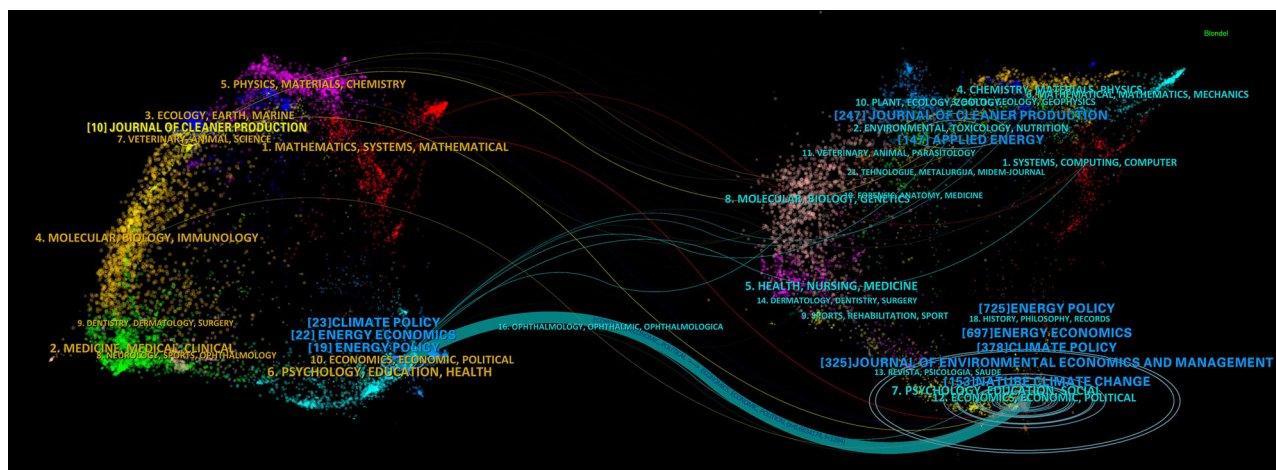


Fig. 6 Dual-graph overlay atlas of Journals based on the WOSCC database.

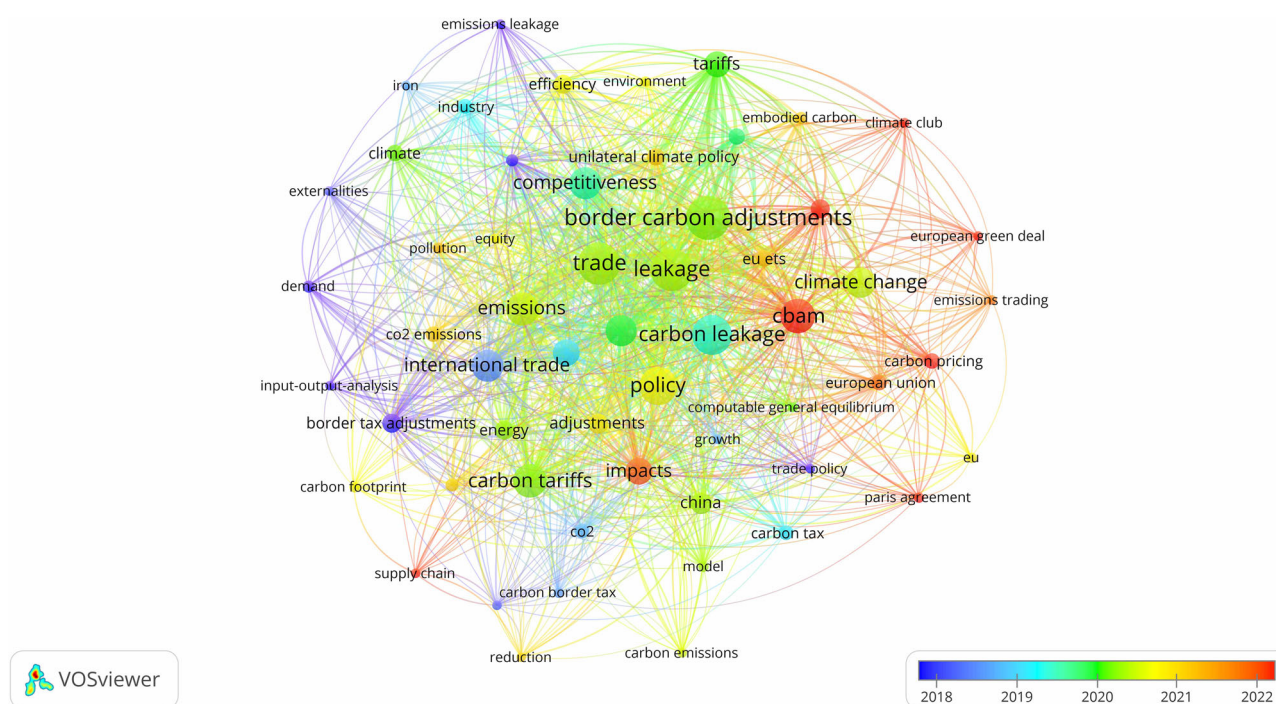


Fig. 7 Keyword co-occurrence network based on the WOSCC database.

2017: China's Carbon Market Pilot

China initiated its carbon market pilot program with the “National Carbon Emissions Trading Market Construction Plan” (Power Generation Industry)⁶. This introduced “carbon pricing” and reflected China’s growing engagement in BCA research (Chen and Guo, 2017; Xu et al., 2017).

- (2) Deepening Development Period (2018–2021)

2019: European Green Deal

The European Commission unveiled the “European Green Deal” aiming for carbon neutrality by 2050 and proposing CBAM to mitigate carbon leakage risks⁷. The policy has stimulated discussions on policy details such as “model” (Zhu et al., 2020), “carbon footprint” (Ortiz et al., 2022), and “efficiency”, with “EU” emerging as a key regional policy term (Evans et al., 2021; Fragkos et al., 2021).

2021: China's National Carbon Market Launch

Following pilot programs, China established a unified national carbon market, initially covering the power generation

industry, with plans to expand to high-emission sectors like cement, steel, and electrolytic aluminum⁸. This reflects the institutional exploration of developing countries in participating in global climate governance (Eicke et al., 2021).

- (3) Mechanism Maturity Period (2021–2023)

In July 2021, the European Commission released the CBAM draft, outlining a transitional period (2023–2025) and full implementation by 2026⁹. CBAM became law in May 2023, requiring importers to declare product carbon emissions and purchase certificates¹⁰. This triggered debates on “CBAM” (Lin and Zhao, 2023), “emissions trading”, and “climate club” (Tagliapietra and Wolff, 2021).

References co-citation analysis. Co-citation analysis is defined as the relationship formed when two documents are jointly cited by a third document (Chen, 2006). Using CiteSpace, we analyzed 300 articles with 10,624 cited references, generating 64 clusters (Fig. 9),

CiteSpace, v. 6.4.R1 (64-bit) Advanced
November 15, 2024, 11:14:39 AM CST
WoS: C:\Users\DT\Desktop\WOS\citespace-0101\data
Timespan: 2009-2024 (Slice Length=1)
Selection Criteria: g-index (k=25), LRF=2.5, L/N=10, LBY=5, e=1.0
Network: N=314, E=1191 (Density=0.0242)
Largest CCs: 305 (97%)
Nodes Labeled: 1.0%
Pruning: Pathfinder
Excluded:

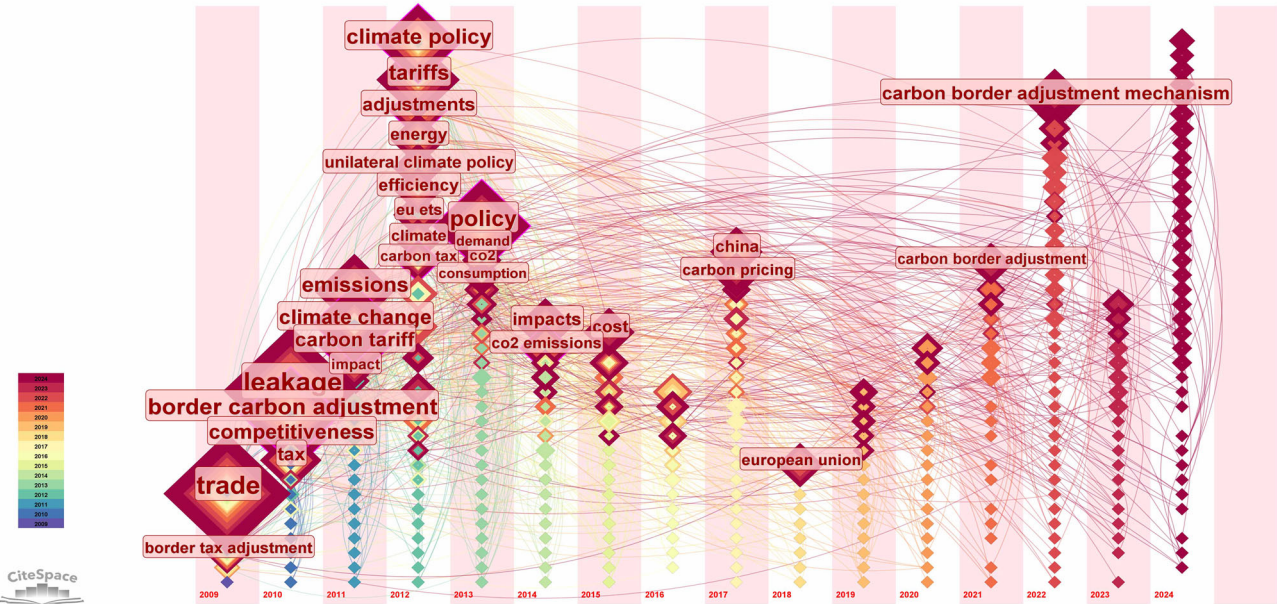


Fig. 8 Time-zone map of keyword co-occurrence based on the WOSCC database.

CiteSpace, v. 6.4.R1 (64-bit) Advanced
November 12, 2024, 10:16:10 AM CST
WoS: C:\Users\DT\Desktop\WOS\citespace-0101\data
Timespan: 2009-2024 (Slice Length=1)
Selection Criteria: g-index (k=25), LRF=2.5, L/N=10, LBY=5, e=1.0
Network: N=555, E=1474 (Density=0.0086)
Nodes Labeled: 1.0%
Pruning: Pathfinder
Modularity Q=0.8034
Weighted Mean Silhouette S=0.9166
Harmonic Mean(Q, S)=0.8563
Excluded:

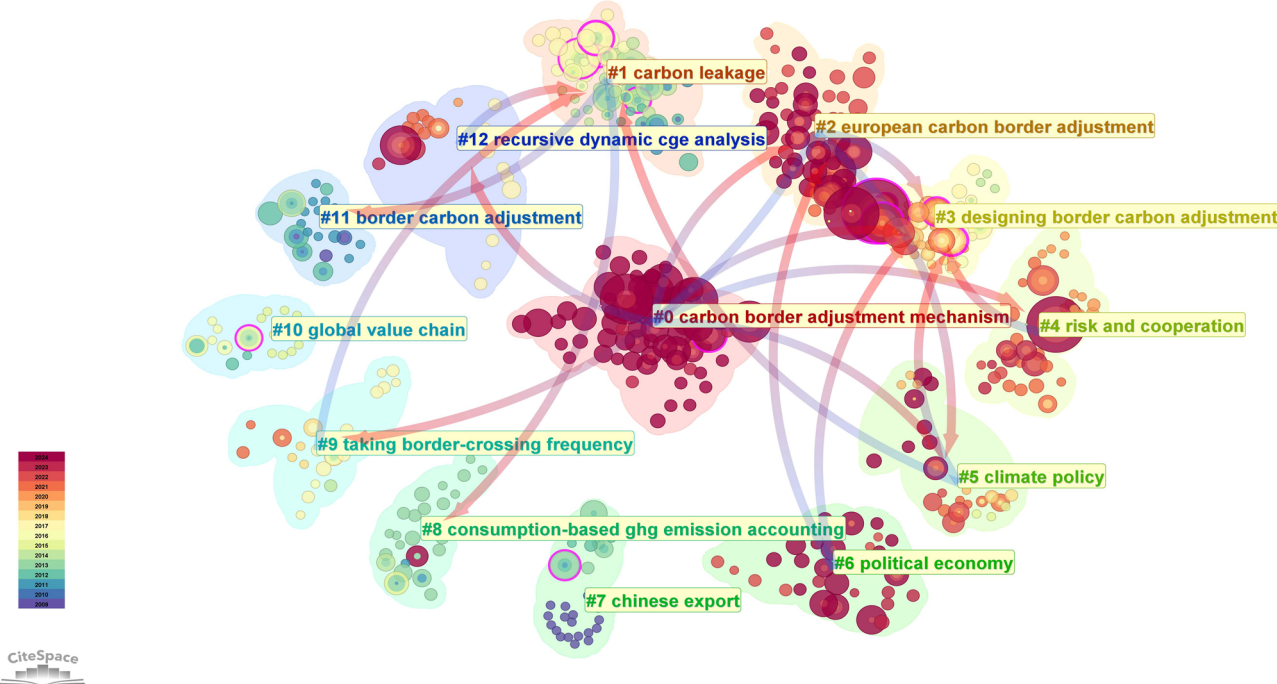


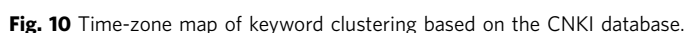
Fig. 9 Cluster diagram of co-cited literature based on the WOSCC database.

of which 13 key clusters were identified(Blashfield and Aldenderfer, 1978). Parameters were set with references as nodes ($K = 25$) and clustered via the LLR algorithm. In Fig. 9, node size reflects citation frequency, node color denotes temporal distribution (red: high-

burst; purple circles: centrality > 0.1), and inter-cluster connections reveal thematic dependencies (Chen, 2006). Cluster #0 (“carbon border adjustment mechanism”) dominates the network with dense purple-red nodes, confirming its centrality as a research

The effectiveness of BCA as a tool to address carbon leakage and competitiveness concerns has been extensively examined (#1, #5, #7, #11, #12): First, Branger and Quirion (2014a) suggested that well-designed BCA policies could cost-effectively mitigate carbon leakage, with subsequent meta-analysis of 310 leakage rates indicating a 6-percentage-point reduction under BCA implementation (Branger and Quirion, 2014b). Sectoral analyses further revealed BCA's stronger leakage reduction in steel industries compared to mineral sectors (Kuik and Hofkes, 2010). Of course, there is no perfect policy tool, and BCA can effectively reduce carbon leakage, but the scope of global cost

The global impacts of BCA, particularly the EU's CBAM, reveal three critical dimensions (#0, #4). First, carbon-intensive industries and developing economies face disproportionate burdens—GTAP-e 11.0 and TOPSIS models indicate significant GDP and welfare losses in major steel-trading nations (Shuai et al., 2024), while energy-intensive sectors in both developing and developed economies experience asymmetric disadvantages relative to policy-imposing regions (Deng et al., 2024). Second, regional analyses identify Eastern European (Balkan states) and African economies (Mozambique, Zimbabwe, Cameroon) as most



vulnerable, with Morocco and Tajikistan also exhibiting high socioeconomic sensitivity (Magacho et al., 2024). Finally, risk-index assessments confirm Africa's heightened exposure across scenarios, where emission-intensive industries and national economies face systemic vulnerabilities (Eicke et al., 2021). These findings collectively underscore the spatially heterogeneous consequences of BCA implementation.

Post-implementation responses to BCA reveal three strategic dimensions (#2, #6). First, WTO disputes over BCA legality may trigger trade retaliation, with energy exporters favoring reciprocal tariffs to offset EU measures and enhance product competitiveness—though such actions risk damaging trade partnerships without fully neutralizing EU industrial gains (Clora et al., 2023; Fouré et al., 2016; Lim et al., 2021). Second, cooperative strategies prove more sustainable: dynamic game theory models suggest active stakeholder engagement (e.g., EU dialogue, low-tech advancement, market diversification, and domestic carbon pricing) can mitigate BCA impacts while improving cost efficiency (Huang et al., 2022; Ren et al., 2023). Finally, EU-centric analyses propose predictive frameworks to gauge global positions—evaluating trade dependencies, carbon intensity, WTO litigation tendencies, public climate sentiment, and innovation capacity—while exploring domestic political incentives and citizen-driven policy support (Jakob, 2023; Overland and Sabyrbekov, 2022; Sabyrbekov and Overland, 2024).

Analysis based on CNKI and the preprint site arXiv

Analysis of BCA development in China based on CNKI. Figure 10 (manually translated from Chinese) presents the results of a temporal cluster analysis of CNKI keywords, revealing a three-phase evolution in China's BCA research through keyword dynamics, while offering a Chinese scholarly perspective for this review (Yan et al., 2023).

Phase 1 (2009–2015): High-frequency keywords such as “BCA”, “climate change”, “international trade,” and “counter-plan” epitomized Chinese academia's passive responsiveness to external pressures. Research centered on defensive responses to Euro-American BCA measures, primarily relying on WTO rule-based compliance analysis, yet most studies remained confined to interpretive levels (Zhao and Guo, 2013). The dominant paradigm employed qualitative assessments using a hybrid “bibliometric + expert consultation” approach, with a scarcity of systematic empirical case studies (Yu, 2013). Notably, due to the absence of domestic firm-level carbon data, studies often constructed multi-regional models using OECD inter-country input-output tables, resulting in significant contextual mismatches (Lin and Li, 2012).

Phase 2 (2015–2020): Literature output during this period exhibited a pronounced trough, with annual CNKI publications dropping to single digits. However, the emergence of keywords like “carbon finance” and “carbon pricing” indicated a shift in focus toward domestic carbon market development and international rule alignment mechanisms (Zhang et al., 2016). Additionally, there was a marked increase in the application of CGE models, simulating BCA impacts on China's GDP (Li and Wang, 2016).

Phase 3 (2020–2024): Following the explicit articulation of “carbon peak” and “carbon neutrality” strategic goals, over 80% of studies incorporated these as strategic contextual parameters for BCA research (Zhang, 2021). The prevalence of the keyword “coping suggestion” confirmed the diffusion of dynamic CGE models and MRIO analysis, with enhanced parameter estimation precision (Bo et al., 2024). Core concepts such as “carbon markets”, “carbon footprints,” and “digital finance” revealed ongoing efforts to construct an integrated analytical framework linking BCA and domestic carbon markets (Deng and Yin, 2022).

The evolution of research foci, as evidenced by keyword dynamics, reveals China's BCA scholarship is transitioning from responsive adaptation to proactive institutional innovation within the global climate governance architecture. When contextualized against international counterparts—where EU studies emphasize technical refinement of compliance mechanisms (Overland and Sabyrbekov, 2022) and US research explores value chain carbon cost internalization (Leonelli, 2023)—China's emerging research paradigm may offer referential pathways for economies navigating common governance dilemmas during low-carbon transition.

Analysis based on preprint site arXiv. Preprints offer emergent discourse analysis for frontier policy debates (Silagadze, 2023). In the BCA field, there are a total of seven articles, among which three were published before 2020. Zafar (2013) found that migrating to 4 G services could reduce carbon emissions by 63% for network operators, thereby demonstrating how technological transitions can align with BCA policy objectives while bringing further economic benefits. Farrahi Moghaddam et al. (2013) proposed IIGHGINT: A generalization to the modified GHG intensity universal indicator toward a production/consumption insensitive BCA. Schofield et al. (2016) presented a baseline-free method to identify responsive customers on dynamic time-of-use tariffs. The remaining 4 newer articles mainly focused on technological innovation and emission reduction. Gupta et al. (2025) discovered that smarter charging habits could reduce costs and carbon emissions for individual electric vehicle owners without significantly altering behavior or sacrificing user preferences. Becker et al. (2025) investigated the effect of electric vehicles, heat pumps, and solar panels on low-voltage feeders using evidence from smart meter profiles. Lee et al. (2022) explored reinforcement learning-based cooperative P2P power trading between DC nanogrid clusters with wind and PV energy resources. Wozny et al. (2023) proposed addressing carbon leakage challenges through methods inspired by CBAM and Climate Clubs, demonstrating the effectiveness of their approach by comparing simulated outcomes to representative concentration pathways (RCP) and shared socioeconomic pathways (SSP).

Research frontier

International frontier forecasting based on WOSCC. To further deepen the exploratory analysis of research frontiers, this study will conduct in-depth mining of the latest clustering outcomes (Cluster 0 and Cluster 6) generated through co-citation clustering of literature in the WOSCC database as independent datasets. With the co-occurrence frequency threshold set to 1, the latest chronological sequence diagrams of keywords are presented in Figs. 11 and 12. Based on the keyword co-occurrence diagram, future research directions are classified into five focal points.

The prominence of keywords including “climate clubs”, “EU CBAM”, “Paris Agreement”, and “developing countries” signals intensifying debates on multilateral rule-making and policy coordination. Implementing nations in the future may employ necessity tests to position BCA as the “least trade-restrictive” climate measure, while proportionality tests could cap BCA tax levels to mitigate carbon leakage risks. A potential WTO “climate exception clause”¹¹ might legitimize science-based BCA frameworks. Climate clubs require critical evaluation of their compliance with the Paris Agreement's “common but differentiated responsibilities”¹² principle to prevent North-South divisions (Tagliapietra and Wolff, 2021). Furthermore, existing studies predominantly focus on developed nations; future research should analyze heterogeneous developing countries, simulating BCA trade impacts on varying economic development levels and assessing differential export repercussions (Chu et al., 2024). High

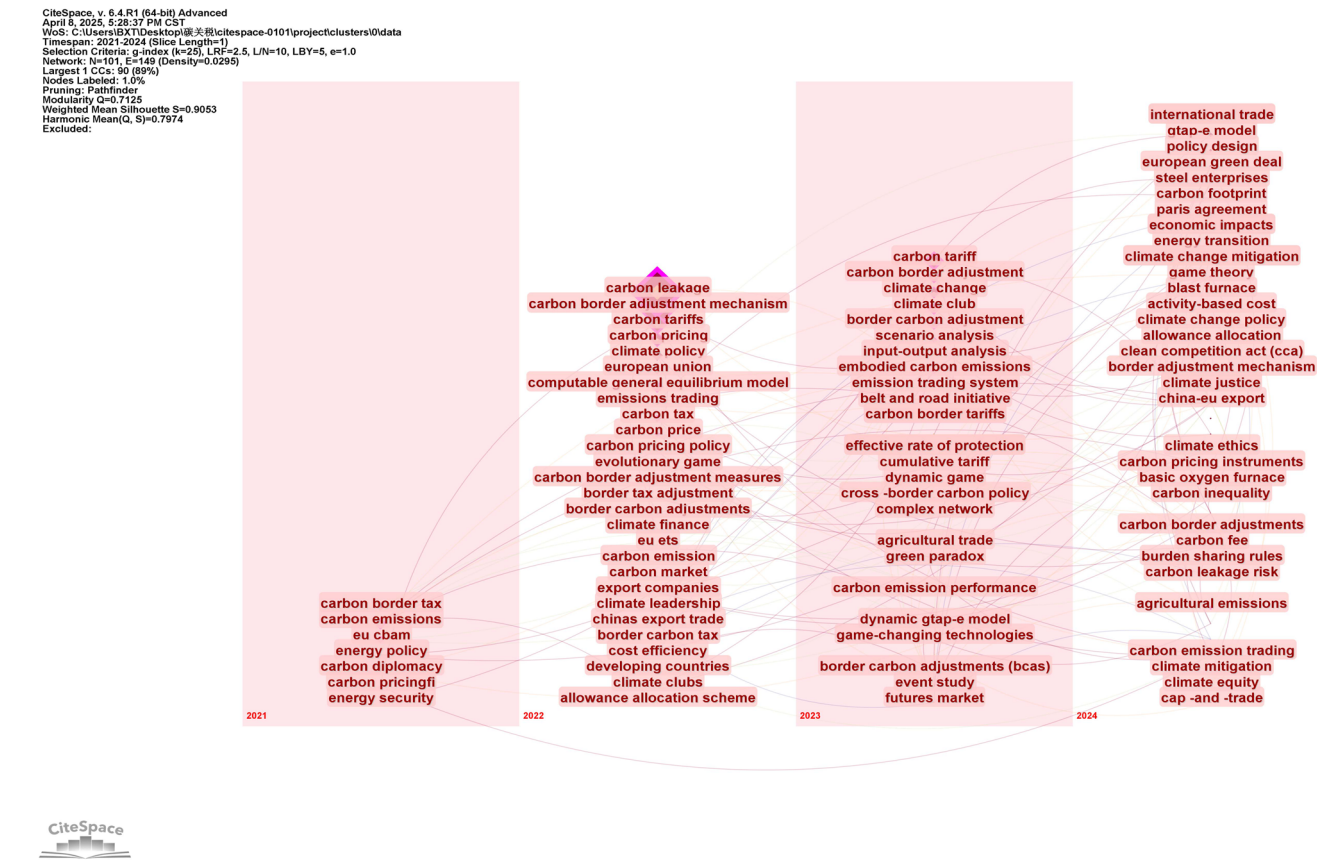


Fig. 11 Keyword Time-Zone map based on re-analysis of cluster 0 results from WOSCC literature co-citation.

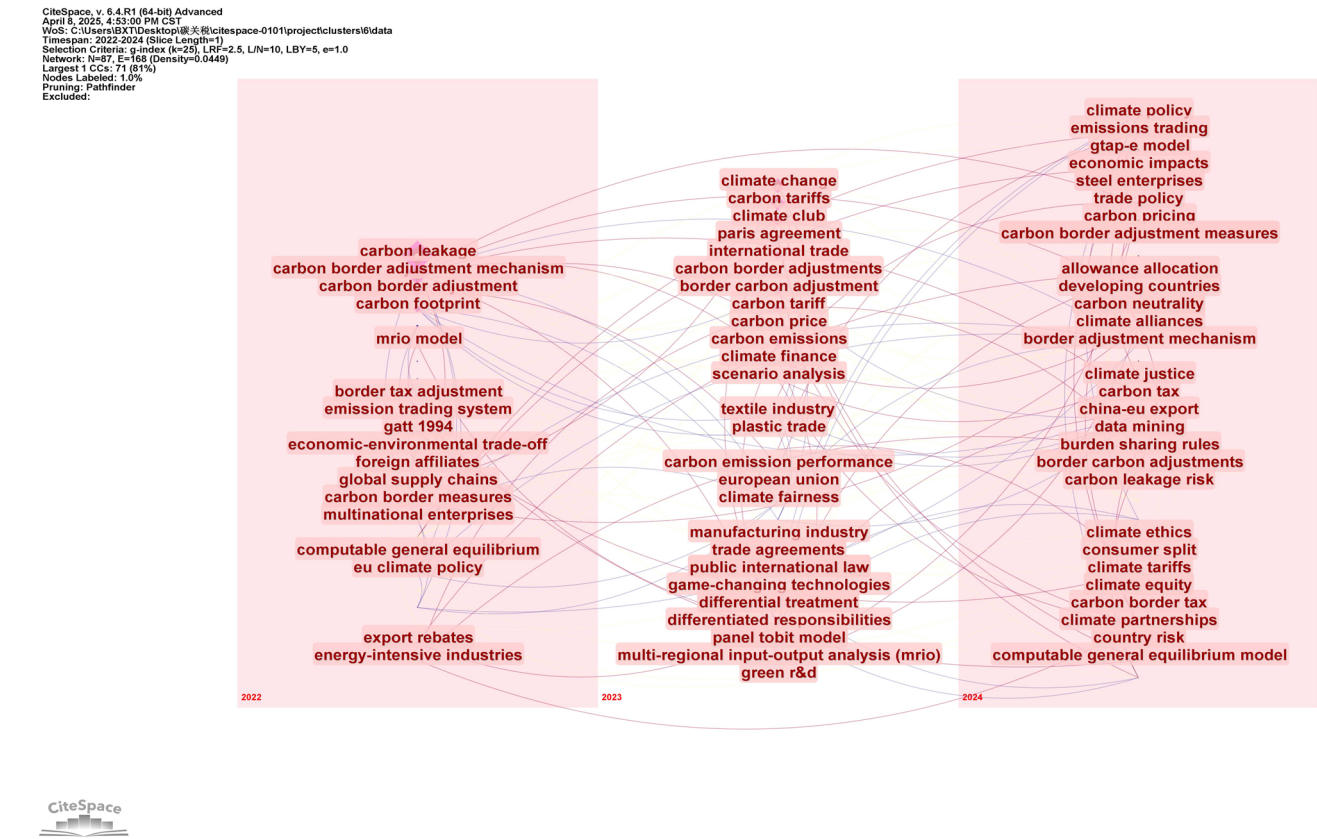


Fig. 12 Keyword Time-Zone map based on re-analysis of cluster 6 results from WOSCC literature co-citation.

Table 5 Latest keywords in 2024.

Count	Year	Keywords	Count	Year	Keywords
1	2024	Green economy	1	2024	Green trade barriers
1	2024	Digital finance	1	2024	Green innovation
1	2024	Embedded emissions	1	2024	Carbon sink
1	2024	Bibliometrics	1	2024	Reporting obligations
1	2024	Dual carbon goals	1	2024	Free allowances
1	2024	Friend-shoring outsourcing	1	2024	Low-carbon standards
1	2024	Scenario development	1	2024	Cooperation pathways
1	2024	Welfare level	1	2024	Cross-border data flow
1	2024	Carbon equity	1	2024	Domestic taxes and fees
1	2024	Entropy weight method	1	2024	Carbon forecasting

EU trade-dependent nations could model carbon cost pass-through capacities (Beaufils et al., 2023; Kitetu and Ko, 2024). Developing countries might also establish climate alliances or innovate South-South cooperation mechanisms to pursue international policy harmonization.

The prevalence of keywords including “steel enterprises,” “plastic trade,” and “global supply chains” underscores sector-specific policy refinement needs under evolving BCA mechanisms (Rübbelke et al., 2022). While the EU CBAM currently targets six sectors (iron/steel, aluminum, cement, fertilizers, electricity, hydrogen) as a foundational framework (Pató et al., 2022), future BCA frameworks could refine three research priorities: (1) Industry expansion to high-leakage-risk sectors like glass and ceramics, guided by national industrial profiles (Hancock and Wollersheim, 2021). (2) Pricing mechanism innovations combining long-term fixed rates for cost stability with short-term floating rates reflecting market dynamics. (3) Regulatory upgrades extending emission scopes to full lifecycle analysis, implementing multi-benchmark systems with dynamic defaults for data-deficient firms, and enforcing tiered supply chain disclosures with carbon transfer coefficients (Jia et al., 2025). Enhanced third-party verification protocols featuring cross-checks and fraud penalties further complete this framework (Li et al., 2023).

The prominence of keywords including “climate justice,” “carbon inequality,” and “burden-sharing rules” underscores accelerating discourse on ethical governance frameworks (Mintz-Woo, 2024). Future systematic solutions could evolve through three dimensions: First, distributive justice via dynamic Carbon Debt Index (CDI) models—integrating historical emissions, GDP per capita, and climate vulnerability—to enable algorithm-driven BCA tax adjustments (Li et al., 2023). Second, procedural justice requires multinational BCA ethics committees to audit policy marginalization effects and arbitrate carbon tariff disputes, while mandating Climate Justice Funds to oversee developed nations’ financial commitments. Third, restorative justice through quota-linked technology transfers, exemplified by EU-led “Technology for Carbon Quotas” programs granting CBAM fee reductions to developing countries adopting certified low-carbon solutions (Perdana and Vielle, 2022).

Keywords like “carbon pricing,” “carbon fees,” “cap-and-trade,” “export companies,” and “futures market” represent the emergence of new policy tools and their economic implications (Hamaguchi, 2024; Shen et al., 2023). Future advancements are anticipated to prioritize three trajectories: First, quantifying the “volatility suppression effect” through EU ETS-BCA interaction analyses will likely dominate research agendas, particularly in assessing how declining free quotas shape carbon price stability, supported by liquidity management tools such as quota reserve pools. Second, carbon tariff futures contracts with cross-cycle hedging mechanisms are expected to mitigate cost risks for export-dependent industries, contingent on integrating blockchain-enabled smart contracts into

MRV systems for automated clearing and transparency. Third, embedding climate model projections into actuarial frameworks is foreseen to enable carbon tariff insurance derivatives, accelerating low-carbon transitions through refined risk pricing (Li et al., 2024). Collectively, these innovations are poised to reduce transaction friction while aligning financial mechanisms with climate imperatives.

Emerging analytical tools, including “CGE Model,” “GTAP-E Model,” and “MRIO Model,” signal future breakthroughs in empirical and technical domains (Lin et al., 2024). First, simplified BCA policy response models for developing countries—operable with limited export-sector emission data and historical carbon prices—could bridge empirical gaps in Southeast Asian contexts. Second, technical integration of MRIO into dynamic GTAP-E frameworks is expected to simulate BCA’s dual-phase impacts on global supply chains, while complex network models may enable real-time tracking of hydrogen/CCUS technology diffusion via low-carbon diffusion maps (Li et al., 2023). Third, CBAM exemption mechanisms could evolve through technology-industry correlation matrices, automatically excluding sectors surpassing zero-carbon technology penetration thresholds. Finally, multimodal AI systems integrating ERP data with regulatory databases are projected to automate carbon accounting and CBAM reporting, revolutionizing compliance workflows.

Frontier supplement based on Chinese perspective. This study utilized CiteSpace to extract the latest keyword data from CNKI’s BCA-related literature (Table 5), supplementing global frontier predictions with insights from Chinese research perspectives. Future investigations may focus on synergistic effects between “digital finance” and “dual carbon goals,” exploring blockchain-enabled optimization of cross-border carbon data traceability and automated BCA settlements via digital currencies (Shi et al., 2024). AI-driven dynamic “carbon forecasting models” could emerge as innovative tools to enhance “free allowance” allocation and policy resilience design. Compared with conventional carbon pricing mechanisms, “green technological innovations” (e.g., hydrogen steelmaking) and “carbon financial derivatives” (e.g., green bonds linked to carbon futures) may facilitate digital governance paradigm upgrades, offering technical references for global carbon markets (Ju and Liu, 2024).

Differentiated BCA designs can employ multi-indicator quantitative methods such as the “entropy weight method” to balance regional development and emission reduction targets, for instance, by integrating “carbon sink compensation” with tiered taxation mechanisms (Zhang et al., 2025). At the industrial level, synergies between “low-carbon standards” and technologies (e.g., full life cycle accounting of new energy vehicle batteries) may expedite international mutual recognition processes. The “friend-shoring outsourcing” cooperation model could provide developing countries with strategies to navigate green trade barriers while promoting the establishment of regional standard alliances (Pan and Lu, 2024).

The integration of cross-border data compliance management with lightweight carbon accounting tools could support developing countries in jointly implementing carbon sink trading and technology-for-carbon-credit swaps (e.g., clean energy in exchange for carbon credits). A flexible cooperation framework may replace the rigid climate club model, permitting differentiated emission reduction pathways while utilizing “scenario modeling” to anticipate policy shocks (Li and Liu, 2024). Such mechanisms hold potential for mitigating carbon cost transfer risks and facilitating the evolution of a multilateral low-carbon regulatory network (Li, 2024).

Conclusions and limitations

This study employs bibliometric tools (VOSviewer/CiteSpace) to analyze publications from the WOSCC, CNKI, and arXiv databases, offering a systematic overview of BCA research. Leveraging data from WOSCC, we constructed knowledge network maps spanning 46 countries, 464 institutions, 712 authors, and 122 journals. A keyword timeline analysis revealed three distinct policy-driven phases in BCA evolution: (1) EU/US BCA framework development (2009–2017); (2) China’s national carbon market implementation (2018–2021); (3) institutionalization of the CBAM (2021–2023). Literature-based co-citation clustering identifies five research hotspots—BCA design, policy effectiveness, socioeconomic impacts, supply chain challenges, and post-implementation strategies—revealing BCA’s evolution from unilateral climate tools to contested global governance instruments. Significantly, CNKI analysis demonstrates China’s paradigm shift: early WTO-compliance studies (2009–2015) transitioned to carbon market establishment (2016–2020), and subsequently to the integration of the “dual-carbon” strategy with digital finance, offering a replicable model for developing economies. Concurrently, arXiv contributions highlight technological solutions, such as smart EV charging, which reduces carbon emissions.

Future frontiers prioritize: (1) Multilateral rule game and political coordination to resolve the North-South gap; (2) Policy refinement incorporating additional industries; (3) climate justice frameworks; (4) Technological innovation of AI compliance systems, blockchain carbon derivatives and hybrid technology innovation; (5) Advances in quantitative analytical tools. Furthermore, emerging economies are seeking context-specific solutions, such as China’s unique innovations in digital finance and South-South alliances.

In summary, this study is the first to systematically review the research hotspots and development pathways in the BCA field, not only revealing the correlation between policy evolution and academic debates, but also providing clear directions for scholars’ future research. By comparing differences between international literature (mature policy systems) and Chinese literature (nascent policy development), this study aims to assist policymakers in establishing phased cognitive anchors and absorbing international experience. Ultimately, this work will promote BCA as a transformative link coordinating climate action, equity, and geopolitical dynamics, providing an empirical foundation for equitable decarbonization strategies.

This study has certain limitations. First, reliance on WOSCC, CNKI, and arXiv databases may exclude relevant studies from non-indexed sources or regional repositories. Second, CNKI’s focus on Chinese scholarship introduces geographic bias, while arXiv’s preprint inclusion risks incorporating non-peer-reviewed insights. Third, co-citation analysis emphasizes influential works, potentially marginalizing emerging perspectives. Future research could incorporate multi-language and regional databases to mitigate geographic bias, establish preprint screening mechanisms to ensure data reliability,

and integrate Altmetrics or qualitative methods to capture emerging trends. Combining expert interviews with bibliometric analysis may balance academic impact assessment and frontier exploration.

Data availability

The data that support the findings of this study are available from the corresponding author, [Yuran Jin], upon reasonable request.

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Notes

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Author contributions

All authors contributed to the research conception and design. Data collection and analysis were conducted by B. The first draft of the manuscript was written by B, and J critically revised the manuscript. All authors read and approved the final manuscript. These authors contributed equally to this work.

Competing interests

The authors declare no competing interests.

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This study did not involve human participants or their data.

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Additional information

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