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Research article

Mapping the landscape of carbon trading & carbon offset research: A global and Indonesian perspective

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Abstract: The escalating annual increase in carbon emissions has posed a significant threat to the environment and human life. In recent years, numerous countries have implemented carbon trading schemes to combat climate change, encourage global cooperation, and promote reductions in emissions. Here, we aimed to explore and delve into the evolving landscape of carbon trading research through in-depth bibliometric and content analysis methods, identifying promising avenues for future research. We identified and retrieved publications on carbon trading and offset from 1993 to 2023 from the Scopus database. By examining 1,994 articles indexed with the keywords 'carbon trading' or 'carbon offsets,' this study offers valuable insights for policymakers, researchers, and practitioners working to mitigate climate change. Our findings revealed four primary clusters: Cluster 1 entailed carbon management and climate change mitigation, cluster 2 entailed innovations and policies in carbon management and sustainable energy, cluster 3 was related to policies related to carbon trading and markets, and cluster 4 was related to integrated energy systems, carbon trading mechanisms, and strategies for achieving a low-carbon economy. Globally, China stands out as a dominant contributor in carbon trading research, followed by the USA, UK, Australia, and Canada. Moreover, Indonesia (as the authors' country) demonstrates increasing involvement, evidenced by 19 publications and collaborations with 12 countries. These findings underscore the need for further, more in-depth research to identify the most effective carbon trading mechanisms specific to Indonesia's unique context. Thematic evolution analysis revealed that carbon sequestration and neutrality were prominent research topics in 2023. A new topic that has emerged is carbon trading policy, which indicates that much research on carbon trading is needed to regulate this matter.

Keywords: carbon trading; carbon offsets; global; Indonesia; bibliometric

1. Introduction

In 2010, energy generation, including electricity and the industrial sector, accounted for over 76% of worldwide emissions [1]. These increased emissions have exacerbated climate change, defined by rising sea levels and more intense weather occurrences. This phenomenon poses severe challenges to both environmental systems and human life. As a result, carbon emissions reduction is an essential component of global sustainable development programs [2].

Carbon trading offers an effective strategy to combat climate change by incorporating economic factors and aligning with the low-carbon goals of Integrated Energy Systems (IES) [3]. The implementation of the Kyoto Protocol in 2005 was a turning point that fostered carbon market growth with the European Union Emissions Trading Scheme (EU ETS) as a pilot [4]. The EU ETS trading volume surged from 94 million to 8.7 billion tons between 2005 and 2013, accounting for 86% of global trade by 2013 [4].

China acknowledged the criticality of climate change impacts of climate change and has taken a multifaceted approach to promote energy efficiency, emission reduction, and a low-carbon economic transition [5]. The initial phase of China's climate action strategy was to conduct a national carbon trading trial in key provinces and cities, including Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, and Shenzhen [6]. This market covers over 20 major polluting sectors, including power generation, cement production, steel manufacturing, and chemical processing; all are significant contributors to national pollution levels [7].

Carbon trading is one of the policy instruments that can reduce greenhouse gas (GHG) emissions more economically and efficiently [8]. This policy is expected to encourage innovations in developing more environmentally friendly technologies and promote the transition to a sustainable economy. Article 17 of the Kyoto protocol and article 6 of the Paris agreement outline one of the steps for climate change mitigation, namely GHG emissions trading [9]. Carbon trading is a market-based mechanism designed to reduce GHG emissions by incentivizing countries or companies that seek to reduce their carbon footprint. Implementing carbon trading involves setting a cap on total permitted emissions, issuing emission certificates, and establishing a market for buying and selling these certificates. The carbon trading system (emission trading system/ETS) is one of the mechanisms established based on the emission cap and carbon pricing to meet the permitted total emission limit [10].

Carbon trading is closely related to carbon tax or emission tax, a tax imposed on companies per unit of emissions released due to the use of fossil fuels or through the carbon market. Moreover, carbon market or emission trading is a place for companies to trade emission quotas at prices set by the market [11]. If regulations related to the carbon tax and carbon market are applied to upstream and downstream producers, then, economically, upstream policies will increase fuel prices, while downstream policies will reduce fuel demand. This will create a complicated dilemma: On the one hand, this policy will reduce fossil fuel sales profits; on the other hand, companies that are not included in downstream policies can buy fuel at cheaper prices, which will increase the level of emissions released into the environment [12].

Over the past three decades, research into carbon trading has witnessed significant growth. This research encompasses diverse topics, from theoretical aspects to practical applications and environmental impact assessments. Researchers investigating the development of China's carbon emissions trading market (CEM) under the "double carbon" (peak carbon emissions and carbon neutrality) goals highlight its achievements and remaining challenges [3,13]. These studies highlight the accomplishments and obstacles encountered in implementing CEM, encompassing market recognition and the accessibility of emissions reduction technologies.

In parallel, researchers in the European Union focus on implementing stricter emission limits and establishing carbon market stability mechanisms [14,15]. A notable example of successful carbon emission mitigation in the United States is California's implementation of a cap-and-trade program designed to reduce emissions while evaluating economic consequences [16]. Moreover, China has emerged as a global economic power and a leading force in carbon trading research. Chinese scholars and policymakers have been at the forefront of exploring innovative carbon trading systems and methodologies for precise emission measurement, rigorous monitoring processes, and practical policy implementation [17].

Furthermore, several bibliometric studies on carbon trading have been conducted, including: a. Blue carbon studies, which reveal the research framework, hotspots, trends, and future directions for the ocean and coastal management [18]; b. Personal Carbon Trading (PCT) studies provide potential, consumption patterns, the need for systematic thinking, and proposed frameworks for individual emission reductions [19]; c. Carbon neutrality studies in the China National Knowledge Infrastructure (CNKI) and WoS databases show differences in focus and levels of collaboration among researchers and institutions from various countries related to carbon emissions, energy efficiency, energy transformation, and other related issues [20]; d. Studies on the alignment between green finance and carbon trading using the VOS viewer framework for bibliometric analysis in the Scopus database [21]; and e. Studies on the role of carbon in international trade, discussing carbon leakage, responsibility avoidance, current status, and future research directions by integrating carbon neutrality theory and carbon trading [22].

Furthermore, a review of academic literature emphasizes the role of research advancements in propelling the development of carbon trading markets while charting new pathways for exploration in carbon economics and finance [23]. Technological advancements are also crucial, as exemplified by research on algorithmic models for carbon trading allocation in specific sectors, such as the F-LNG-E heavy truck industry [24]. Integrating academic and technological progress is paramount for developing effective carbon trading systems.

Additionally, studies demonstrate robust academic endorsement of carbon pricing frameworks. A global survey was conducted among climate policy researchers to assess scientists' agreements and disagreements on six climate policy instruments across disciplines. The most significant correlation with valuing carbon price was the agreement that it successfully curtails energy/carbon rebound and had the possibility for global harmonization [25]. Another survey was carried out to investigate the benefits and drawbacks of carbon pricing, future research directions, and opinion variations among researchers. The study emphasizes carbon pricing's perceived strength in reducing emissions, providing investment incentives, and decentralizing policy, while highlighting disadvantages such as potential regressive effects, low support, and multidisciplinary knowledge gaps [26]. These revelations accentuate the necessity of addressing these deficiencies through interdisciplinary inquiry to guarantee that carbon trading and offset mechanisms are not only efficient but also socially equitable and globally applicable.

Despite its potential, the successful implementation of carbon trading faces significant challenges, particularly in developing countries. A robust and transparent regulatory framework and effective stakeholder engagement are indispensable for successfully integrating carbon trading into a country's policy landscape. The government and research institutions must meticulously consider setting the optimal carbon price, which must be high enough to provide incentives for emission reductions but not too burdensome for the national economy. Flexible carbon prices responsive to market dynamics and technological advances are essential to effectively align environmental and economic needs. Governments must establish an advanced monitoring, reporting, and verification (MRV) system to ensure accurate and reliable data [17]. Implementation also requires broad public support, so education is needed to raise public awareness about the benefits of carbon trading and the importance of emission reductions.

In this article, we aim to map the current research trends on global and Indonesia's carbon trading through bibliometric analysis. In addition, we evaluate academic outputs, identify thematic and methodological trends in carbon trading research, and assess the contributions of various countries to the field, especially Indonesia. We discuss Indonesia's role globally within the broader context of global carbon trading and conduct a comparative analysis of domestic and international carbon trading practices to establish an effective carbon trading mechanism in Indonesia. The identification results provide recommendations for more focused research related to the carbon trading mechanism in Indonesia in the future.

This article's novelty is the application of extensive bibliometric analysis to delineate the research landscape of carbon trading while combining quantitative methods with qualitative content analysis. This approach offers a nuanced understanding of the dynamics, challenges, and opportunities in carbon trade policies globally and in Indonesia.

2. Methods

2.1. Research question

We define the review's scope and formulate research questions (RQs) to guide the exploration.

RQ1: What are carbon trading research's thematic and methodological trends?

RQ2: Which countries are the most productive and collaborative in carbon trading research?

RQ3: How do Indonesian researchers contribute to the publication of global carbon trading research?

RQ4: Based on the thematic evolution, what promising research areas should be explored to refine better carbon trading schemes globally and in Indonesia?

2.2. Database selection

We employed the Scopus database for literature search, which is renowned for its vast and multidisciplinary coverage. This choice aligns with Scopus's reputation as a preferred tool for bibliometric analyses [27]. The bibliometric analysis involved a multi-stage data collection process, detailed in Figure 1. This strategy was adapted from the approach outlined in [28] to enhance clarity and efficiency.

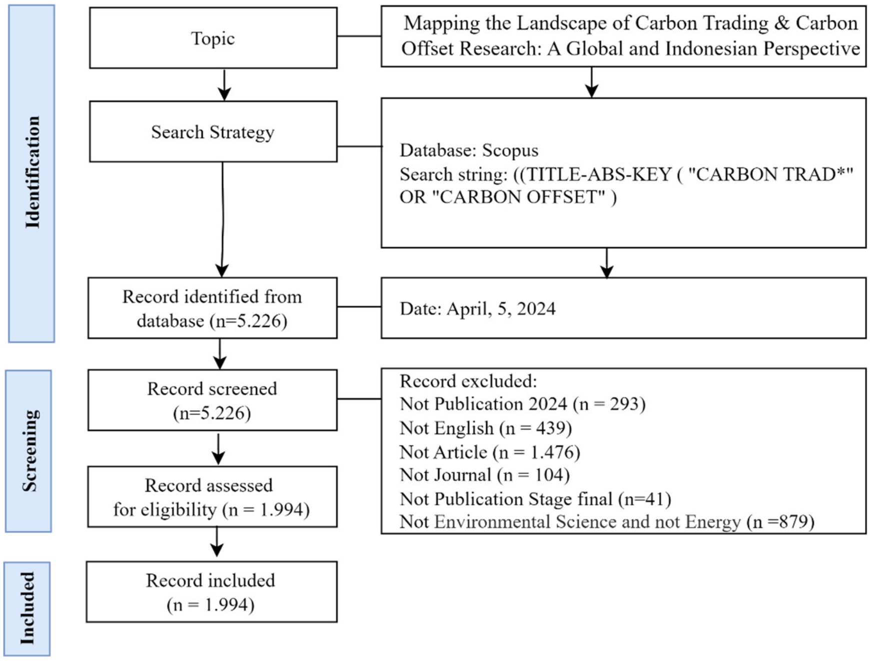


Figure 1. Adapted from PRISMA Flow diagram for carbon trading and carbon offset.

A systematic literature search was conducted in the Scopus between 1993 and 2023. To identify relevant publications, we employed keywords, including "carbon trading" or "carbon offsets" within titles or keywords. Following the application of predefined inclusion criteria, which restricted the analysis to articles and specific source types, a final dataset of 1,994 articles was obtained for further analysis.

2.3. Bibliometric and content analysis

We utilize a two-pronged methodological approach [29] to delineate the research landscape and identify promising avenues for future exploration (Figure 2). The first phase involves a combined descriptive and bibliometric analysis. The bibliometric analysis leverages co-occurrence mapping, three-field plots, and thematic evolution to identify the most relevant publications for subsequent in-depth content analysis. This mapping provides a structured framework for extracting full-text documents from each identified cluster, facilitating comprehensive exploration to address research questions concerning potential future topics. The selection process prioritizes trending and influential topics, informed by key factors like prominent keywords and citation counts visualized within the VOSviewer output.

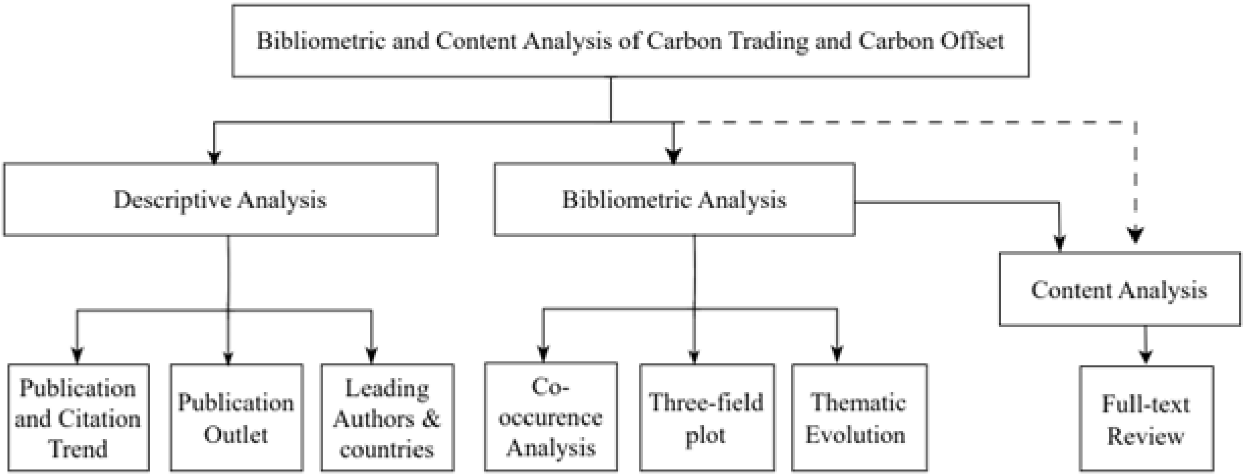


Figure 2. Research structure to answer RQs for carbon trading and carbon offset.

3. Results

3.1. General statistics

Graphs of publication development over time can be useful for assessing the growth of certain research topics [29]. Based on the data obtained, we found that the number of publications experienced a significant increase in the last 30 years, with the Period being from 1993–2023. Figure 3 shows that 2023 had the highest number of publications, namely 415 article titles. This reflects the increasing importance and relevance of the topic under study, which provides an opportunity to contribute to research in this field. In addition, a trend line with an exponential trend fitted to the data produces a significant R-squared value of 0.8906.

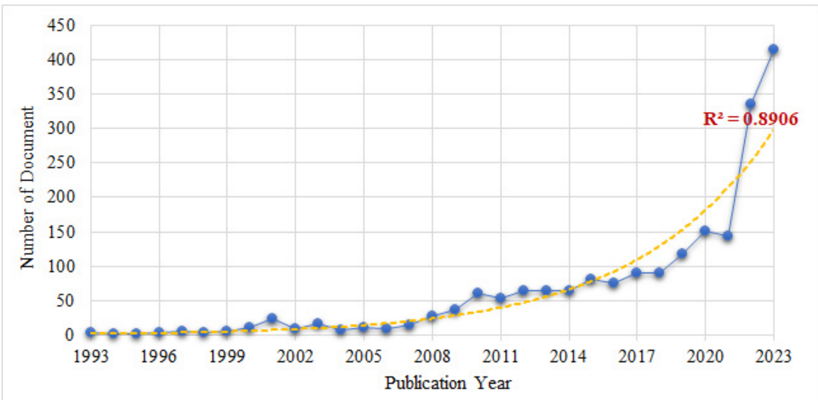


Figure 3. Progress distribution of the number of published publications and the yellow dotted line represents the exponential trend line.

Figure 4 shows a graph of the average number of citations per year. The increase in the number of citations follows a polynomial trend, which indicates that data patterns are curved or discontinuous from a straight linear trend. This often happens with large data sets that contain many fluctuations. As more data becomes available, the trend becomes less linear, and a polynomial trend forms.

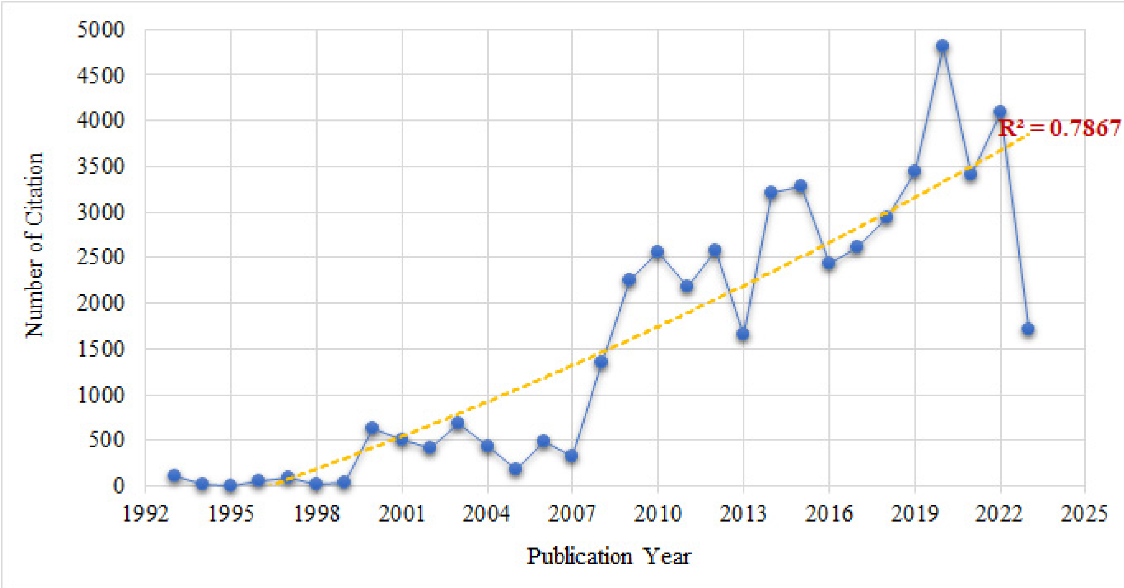


Figure 4. Distribution of publication citations per year with the yellow dotted line representing the polynomial trend line.

In addition, a trend line with an exponential trend fitted to the data produces a significant R-squared value of 0.7867. The overall trend of the graph shows that the number of citations increased around 2000, reaching a peak around 2020. The years 2000, 2010, 2015, and 2022 stand out the most, indicating years of particular interest and importance or significant events related to the analyzed data.

3.2. The distribution of journals

Based on relevant sources, 390 publication titles correspond to this topic. In Table 1, the Top 10 journal titles in the Q1 category and one in the Q2 category are displayed, which are relevant to publishing articles according to the studied topic. In this table, the Sustainability Journal (Switzerland) is the journal that published the most articles, with 147 publications. Moreover, the most influential journal is the Journal of Cleaner Production, which has a total link strength of 331. The most cited journal is the Energy Policy Journal, with an average of 57.6265 citations.

In addition, ten journals are included in the Q1 category, meaning they are included at the highest level of journal quality. The data in Table 1 are metrics accessed using the cite score on Scopus.

Table 1. Sources of relevant journal information.

Sources	Rank	Quartile	NP	TC	Links	Total link strength	Avg. Pub. year	Avg. citations
Sustainability	1	Q1	147	1537	34	150	2020.884	10.4558
J Cleaner Product	2	Q1	144	5511	69	331	2020.063	38.2708
Energy Policy	3	Q1	83	4783	62	282	2014.133	57.6265
Environmental Sci Pollut Res	4	Q1	66	628	34	110	2022.152	9.5152
Energy	5	Q1	65	1859	52	171	2021.169	28.6
Energies	6	Q1	62	505	22	48	2021.145	8.1452
Appl Energy	7	Q1	60	3403	45	251	2018.717	56.7167
Climate Policy	8	Q1	53	1328	47	151	2012.189	25.0566
J Environ Manage	9	Q1	43	1196	31	72	2019.814	27.814
Frontiers Energy Res	10	Q2	37	70	17	26	2022.595	1.8919
Int J Environ Res Public Health	10	Q1	37	388	16	50	2021.378	10.4865

Note: NP: Number of Publication; TC: Total Citation

3.3. Leading authors and collaborations

A total of 5,975 authors have contributed to research on this topic. Of these, 201 authors are collaborative and network with at least one document while 5,774 authors remain unnetworked. These unnetworked authors are grouped into 18 clusters, as illustrated in Figure 5.

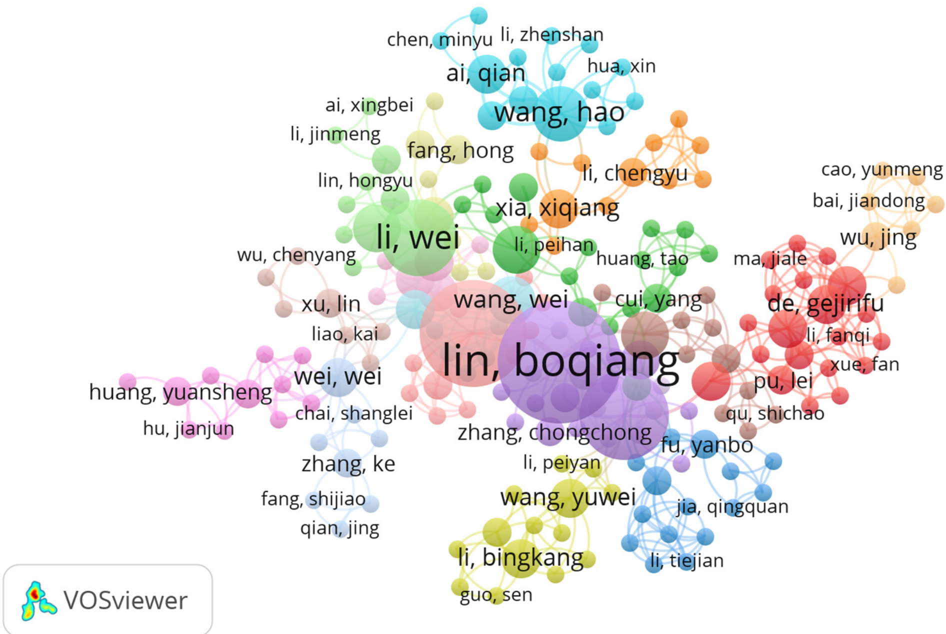


Figure 5. Network visualization of productive and collaborative authors (co-authorship-Author).

Table 2 presents the top six most productive and collaborative authors. Lin Boqiang is the most productive, collaborative, and highly cited author, with 16 publications, a link strength of 17, and an average citation count of 56.375. He is a researcher from Xiamen University, China.

Table 2. Top 6 productive and collaborative authors.

Authors	Rank	NP	TC	Links	Total link strength	Avg. Pub. Year	Avg. citations
Lin, boqiang (China)	1	16	902	10	17	2021	56.375
Jia, zhijie (China)	2	12	670	11	17	2020	51.539
Sun, wei (China)	3	10	480	12	15	2020	48
Li, wei (USA, China)	4	8	411	14	18	2019	51.375
Wang, hao (China)	5	5	53	14	17	2021	10.6
Choi, yongrok (South Korea)	6	4	26	8	9	2020	6.5
Lu, can (China)	6	4	213	4	8	2018	53.25
Tan, zhizhou (China)	6	4	110	7	9	2022	27.5
Wang, wei (China)	6	4	6	18	18	2022	1.5

Figure 6 is provided to clarify Table 2 by illustrating the productive and collaborative authors. The length of the bars indicates the number of publications by the authors mentioned above, and the color indicates the average year of publication from 2018 to 2023. The thickness of the bars denotes the average number of citations (avg. citations).

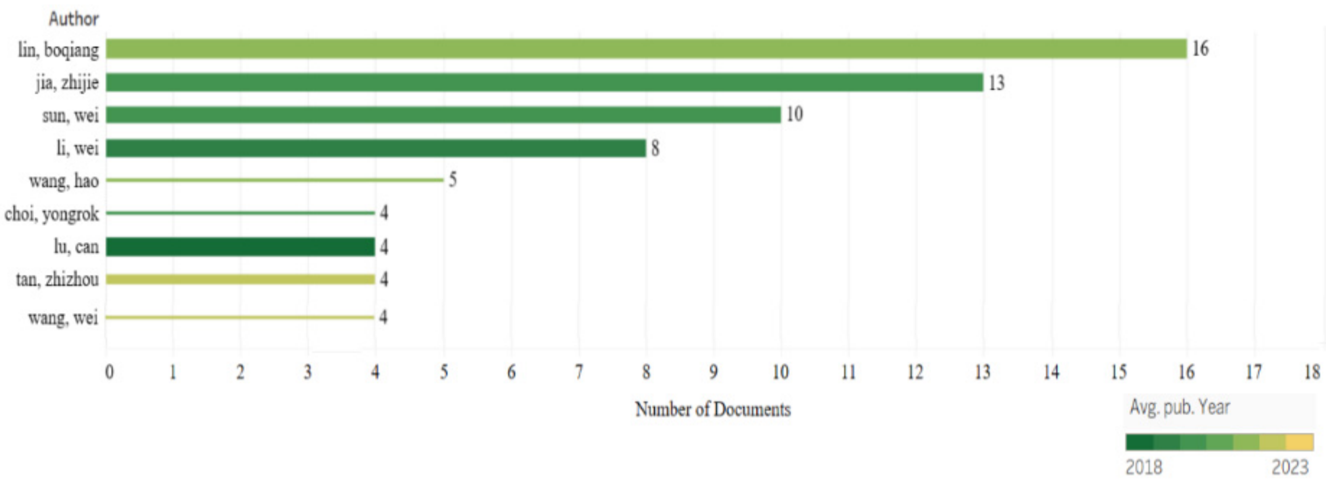


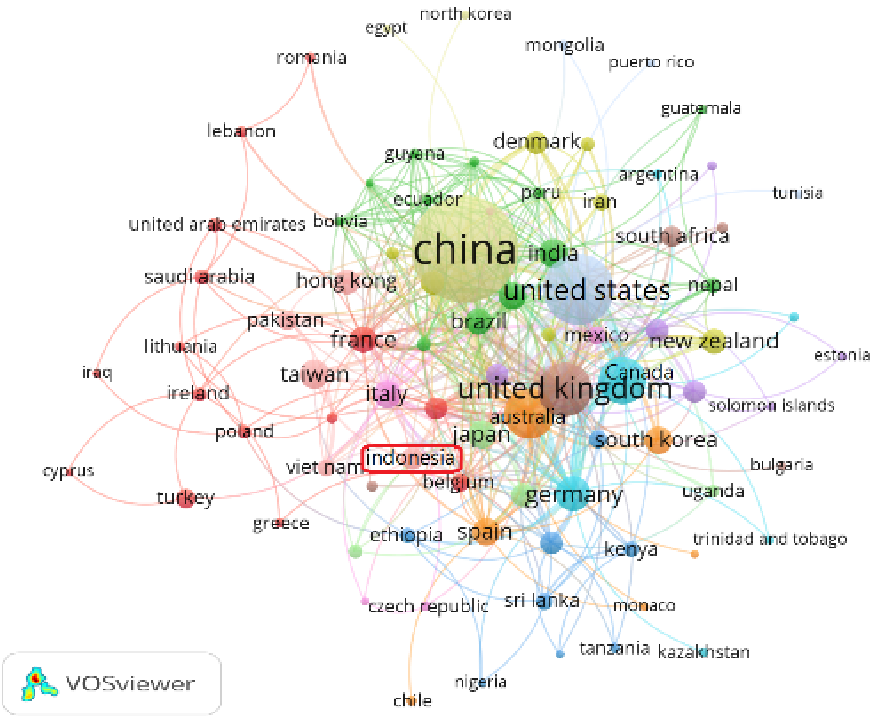
Figure 6. Top 6 productive and collaborative author (co-authorship-author).

The analysis was then conducted with the inclusion of all authors, both those with networks and those without. The results, as shown in Table 3, reveal the Top 6 most productive and non-collaborative authors, predominantly dominated by Chinese authors. However, the list also includes Wang Shanyong (ranked 3rd from Australia), Fan Jin (ranked 5th from the USA), Li Wei (ranked 5th from the USA/China), and Galik Christopher S. (ranked 6th from the USA).

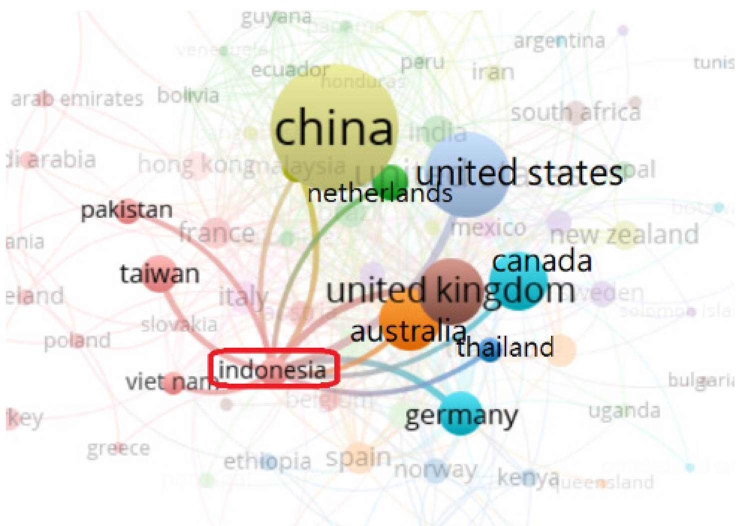
Table 3. Top 6 productive and non-collaborative authors.

Authors (Country)	Rank	NP	TC	Links	Total link strength	Avg. Pub. Year	Avg. citations
lin, boqiang (China)	1	16	902	4	11	2021	56.375
Jia, zhijie (China)	2	13	670	3	9	2020	51.539
Wang, shanyong (Australia)	3	11	241	9	32	2018	21.909
Chen, hong (China)	4	10	219	7	24	2020	21.900
Li, jun (China)	4	10	172	9	30	2018	17.200
Long, ruyin (China)	4	10	219	7	24	2020	21.900
Sun, wei (China)	4	10	480	5	8	2020	48.000
Fan, jin (USA)	5	8	186	5	27	2016	23.250
Li, wei (USA, China)	5	8	411	6	10	2019	51.375
Tang, bao-jun (China)	5	8	328	9	15	2018	41.000
Zhang, yue-jun (China)	5	8	629	2	3	2019	78.625
Galik, christopher s. (USA)	6	7	161	3	7	2013	23.000
Van kooten, g. cornelis (Canada)	6	7	265	1	2	2012	37.857
Wang, lei (China)	6	7	86	7	12	2022	12.286
Zhao, dingtao (China)	6	7	172	5	25	2016	24.571

After data observation and cleaning, 95 countries were identified as contributing to this topic. Of these, 86 countries are networked/collaborative, while 9 are not yet networked. They are grouped into 13 clusters, as shown in Figure 7a and b. Figure 7a provides an overview of the contribution of research samples by country of affiliation, where China has the largest contribution to this research, followed by the United States of America, United Kingdom, Australia, and Canada. Moreover, Figure 7b shows that Indonesia has contributed 19 publication titles and is part of the networked countries, especially collaborating with China.



(a)



(b)

Figure 7. a: Network Visualization of a productive and collaborative country, and b: Network Visualization Indonesian collaboration.

Our analysis revealed China as the most productive and collaborative country, contributing 1,024 publications with a total link strength of 258 (Table 4). However, the Netherlands boasts the highest average citation count at 50.4194. Indonesia, ranked 17th within this dataset, has contributed 19 publications and collaborates with researchers from 12 countries.

Table 4. Top 10 productive and collaborative countries.

Authors	Rank	NP	TC	Links	Total link strength	Avg. Pub. year	Avg. citations
China	1	1024	21203	43	258	2020.86	20.7061
USA	2	346	11671	47	222	2013.835	33.7312
United Kingdom	3	173	6632	46	155	2014.052	38.3353
Australia	4	139	4974	41	114	2015.741	35.7842
Canada	5	119	3574	23	80	2014.849	30.0336
Germany	6	56	2231	26	66	2015.554	39.8393
Taiwan	7	37	585	10	20	2018.973	15.8108
India	8	36	908	24	42	2015.333	25.2222
South Korea	9	33	589	6	15	2017.758	17.8485
Italy	10	31	1387	25	51	2016.419	44.7419
Netherlands	10	31	1563	26	51	2013.484	50.4194
Spain	10	31	638	21	32	2017.065	20.5806
…	…						
Indonesia	17	19	328	12	24	2017.684	17.2632

3.4. Carbon trading research trend mapping

To answer RQ1 on current research trends, we employ the VOSviewer and biblioshiny softwares for co-word analysis. In this method, we utilize author keywords as the unit of analysis and rely on co-occurrence analysis. Co-occurrence analysis enables the examination of primary themes, key topics, or significant concepts within publications [29]. Each keyword is represented as a circular node in the resulting network visualization. The node's size reflects the keyword's weight, meaning larger nodes signify a higher frequency of occurrence. The spatial proximity of keywords indicates their association within the analyzed documents; closer nodes suggest a stronger connection [30].

Based on the analysis results, 5,529 author keywords were found. Subsequently, narrowing down to those occurring at least seven times yielded 149 keywords. Further data cleaning involved merging identical keywords and cross-referencing with the dataset file. Following data cleaning, the keywords were reduced to 130, which were incorporated into the VOSviewer thesaurus. The co-occurrence analysis resulted in a network visualization, as depicted in Figure 8 and Table 6, revealing the presence of 4 distinct clusters/themes.

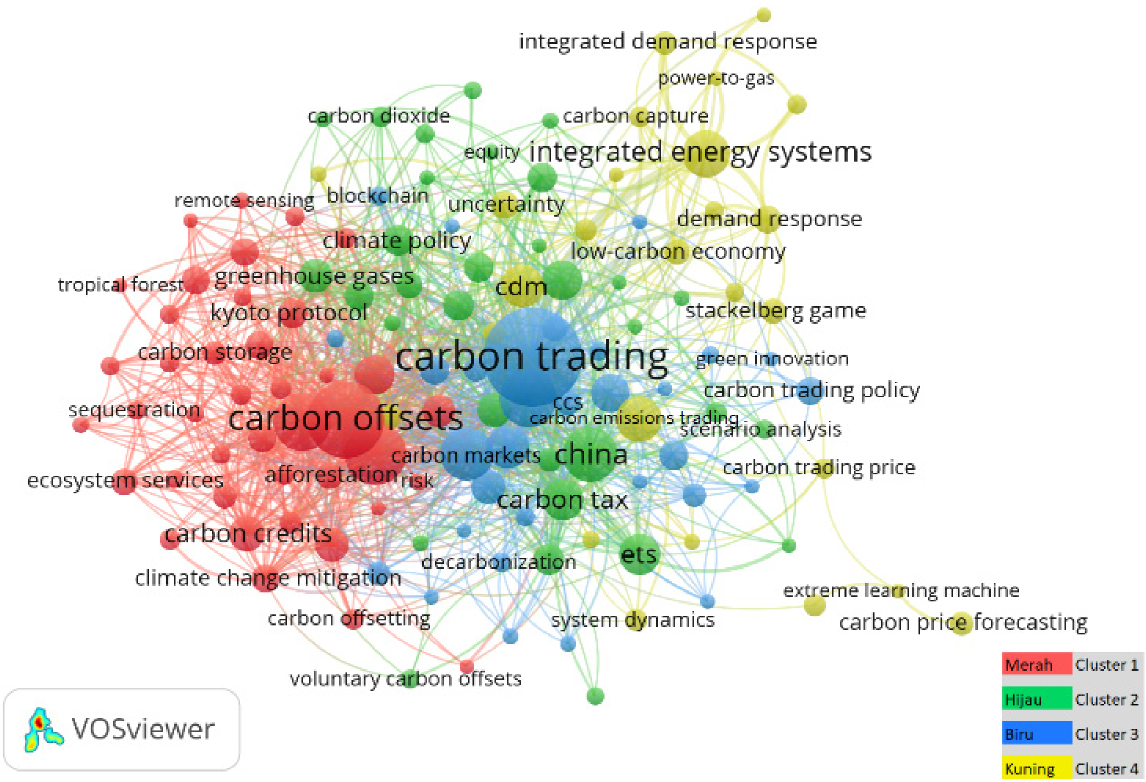


Figure 8. The network visualization of co-occurrence with author keywords appears when a keyword occurs at least 7 times.

Table 6. Main keyword for each cluster.

	Topic label	Most discriminating terms and illustrative titles
C1	Carbon offsets	carbon offsets; climate change; carbon sequestration; clean development mechanism; kyoto protocol; carbon credits; carbon trading; climate change mitigation; redd+; emissions trading, cap-and-trade
C2	Carbon tax	China; biomass; carbon tax; personal carbon trading; carbon trading; carbon offsets; climate policy; sustainable development; emission trading scheme; bioenergy; climate change
C3	Carbon trading	carbon trading; carbon emissions; carbon neutrality; carbon market; carbon emission reduction; carbon price; EU ETS; China; personal carbon trading; climate change; integrated energy system
C4	Carbon trading mechanism	integrated energy system; carbon trading mechanism; carbon emissions trading; carbon trading; uncertainty; demand response; integrated demand response; stackelberg game; low-carbon economy; carbon accounting; carbon price forecasting

The visualization of the 4 clusters is presented in the form of word clouds, each representing themes focused on environmental issues and climate change, particularly concerning carbon emission management. These four clusters illustrate various approaches and strategies in managing carbon emissions, ranging from offset mechanisms and national policies to carbon trading and more complex market strategies, illustrated in Figure 9.

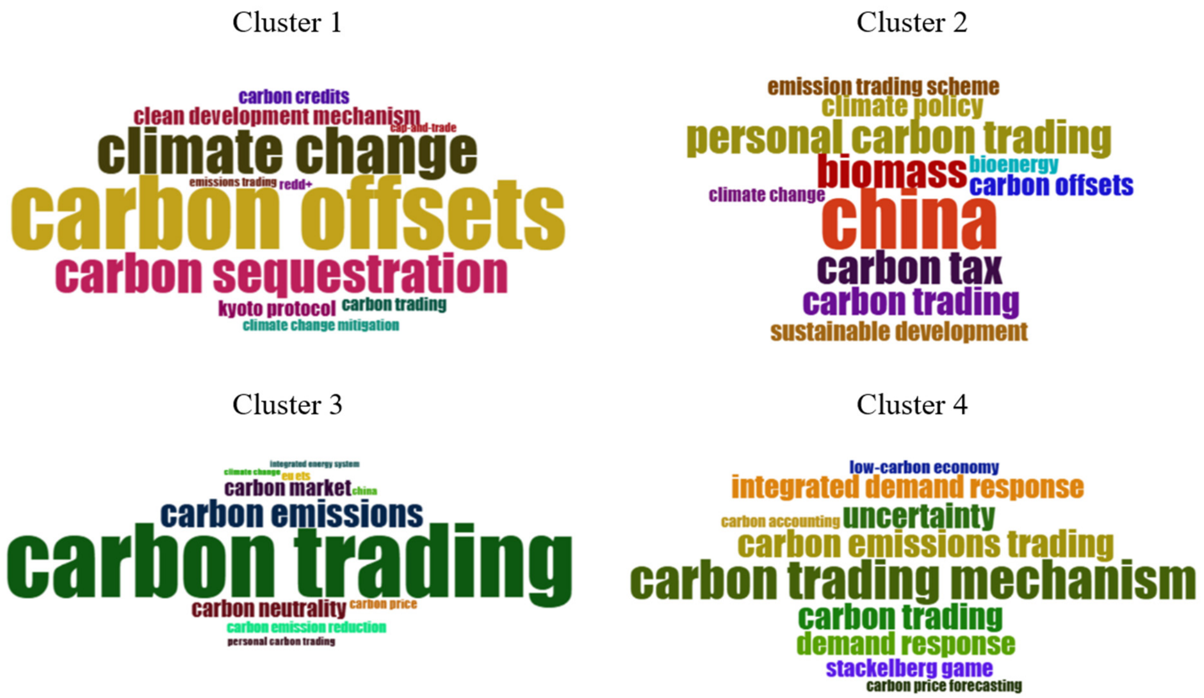


Figure 9. Word clouds of 4 clusters in carbon trading and carbon offset.

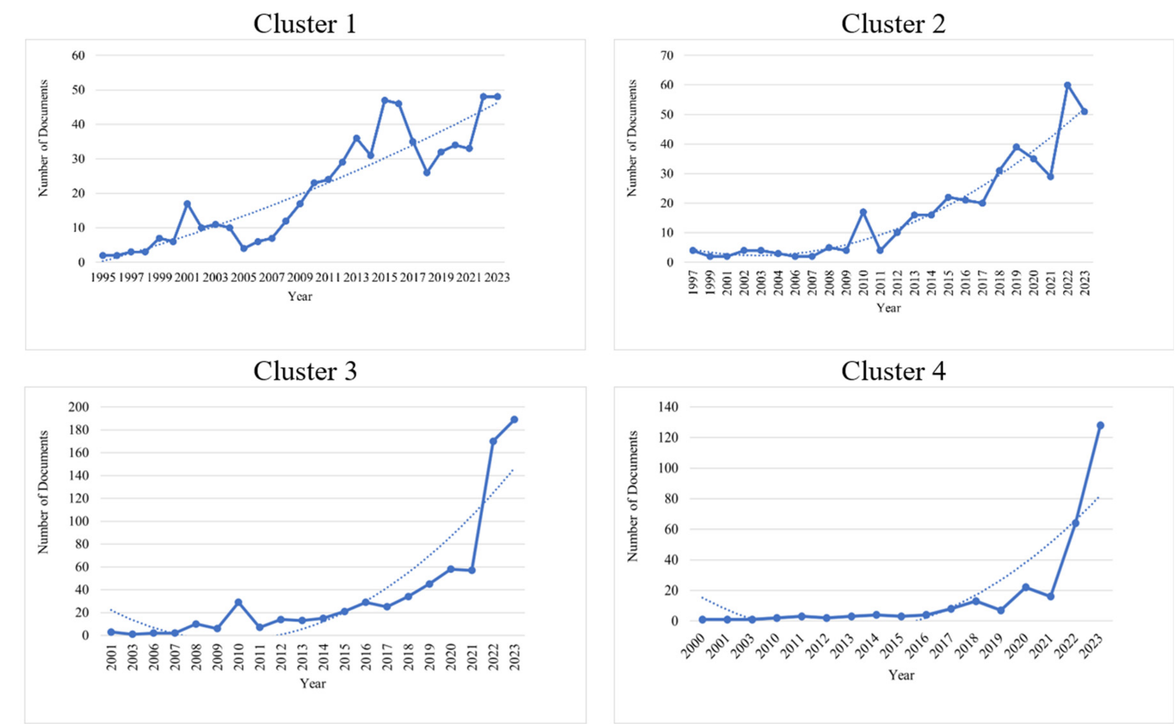


Figure 10. Growth in the number of publications of clusters in carbon trading and carbon offset over time.

The growth in the number of publications within each cluster on the topics of carbon trading and carbon offsetting over time demonstrates varying growth trends. Cluster 1 has exhibited steady growth since 1995, with a significant increase after 2010. Cluster 2 shows a more fluctuating growth pattern but tends to rise sharply after 2014, reaching its peak in 2022. Cluster 3 experienced a sharp surge in publications after 2020, peaking in 2023. This surge is attributed to the growing global urgency surrounding climate change mitigation and the implementation of carbon trading policies. Similarly, Cluster 4 has shown rapid growth since 2018, with notable increases in 2022 and 2023. The graph in Figure 10 illustrates the substantial rise in the number of publications in the field of carbon trading and carbon offsetting, reflecting heightened global awareness and research interest in environmental and sustainability issues.

The key terms in Cluster 1 include carbon offsets, carbon sequestration, and emissions trading, as presented in Table 7. Cluster 1 is the most dominant cluster, with its main theme related to carbon management and climate change mitigation. This theme encompasses various strategies and mechanisms for managing carbon emissions and mitigating the impacts of climate change, including efforts from technical, economic, and policy perspectives.

Table 7. Top 11 terms in cluster 1.

No.	Terms	Frequency	%
1	Carbon offsets	240	28.1
2	Climate change	153	17.9
3	Carbon sequestration	131	15.3
4	Clean development mechanism	57	6.7
5	Kyoto protocol	51	6.0
6	Carbon credits	47	5.5
7	Carbon trading	44	5.2
8	Climate change mitigation	37	4.3
9	Redd+	35	4.1
10	Emissions trading	30	3.5
11	Cap-and-trade	29	3.4
	Total	854	100

Subsequently, to examine the content of these articles, a content analysis was conducted. Table 8 shows that the most cited papers on carbon offsets provide a global perspective on various innovative trends, covering methodology, theory, and thematic areas in efforts to reduce carbon emissions in various countries.

In cluster 2, the keywords most frequently used are China, carbon tax, and greenhouse gases. Generally, the main theme of cluster 2 pertains to innovations and policies in carbon management and sustainable energy. This theme explores the intersection of technology, policy, and strategies to reduce carbon emissions and enhance sustainable energy practices globally, focusing on methods and impacts. The prominence of the keyword “China” indicates that China has conducted extensive research related to carbon emission policies. Table 9 explains the top 11 keywords in cluster 2. The keywords carbon tax, ETS, personal carbon trading, carbon trade, voluntary carbon offsets, and carbon quota focus on various government and market-based instruments designed to regulate and incentivize carbon reduction. These include taxes, trading schemes, and voluntary offsets. When carbon taxes are designed and executed efficiently, they can serve as a potent economic motivator for curtailing carbon emissions, concurrently generating funds to facilitate the shift towards a sustainable, low-carbon economy. Cluster 2 is mostly connected to cluster 3 (Figure 11), especially with the keywords carbon trading, carbon emission trading, and climate change.

Table 8. Top-cited papers on carbon offsets.

Cited	Method	Important Findings	Contributions	Ref
409	- Analyze historical land use patterns, current land use practices, and all general life zone classifications. - The analysis conducted linear and log-linear regressions in Systat 7.0.	Tropical reforestation has the potential to last 40 to 80 years, or even longer, as a carbon offset both below and above the ground.	Imply that replanting has a beneficial effect on offsetting carbon emissions. To reduce the impact of global climate change on carbon absorption, it is necessary to emphasize carbon offset policies in all countries	[31]
164	- Choice Experiments (CE) - Dichotomous-choice CV - Bias - Econometric analysis	Investment in co-benefitting projects and consumer education on these co-benefits can encourage the adoption of voluntary offsets. The value of offsets will increase, and certification regimes will assist in offsetting rising expenses.	The VCO market may provide considerable financial opportunities for biodiversity hotspots, development organizations, sustainable markets, and technology development.	[32]
130	- The retrospective analysis of China's seven pilot carbon trading schemes.	The ideal national ETS would conform to uniform guidelines for allowance distribution, compliance rules, measurement, reporting, and verification.	Investigate potential paths for converting local pilot carbon trading programs into a broad national carbon trading program.	[33]
94	- Modelling aboveground tree growth rate, soil and litter carbon absorption, harvesting and storage losses, and energy conversion efficiency under different conditions.	The strategy to overcome climate change is to look for technology to replace fossil fuels; the development of biomass-based SRWC will become commercially viable in the future.	Stating that if carbon taxes are implemented, SRWC's growth rate will be accelerated, and the price of fossil fuels will rise. SRWC will become more economically attractive as an energy source.	[34]
71	- Describe the current state of the Kyoto Protocol, evaluate the ETS's implementation, and contrast the various approaches. - Linear regressions with the statistical analysis add-in features of Microsoft Excel software to analyze the ETS penalty's efficiency	Since the ETS base year was implemented, carbon emissions have been declining at about 1.58% annually. The ideal penalty for attaining the highest level of carbon reduction is roughly US$90.22 per tonne	Examining the main nations' current GHG emission laws and determining which have met their 2021 targets	[35]

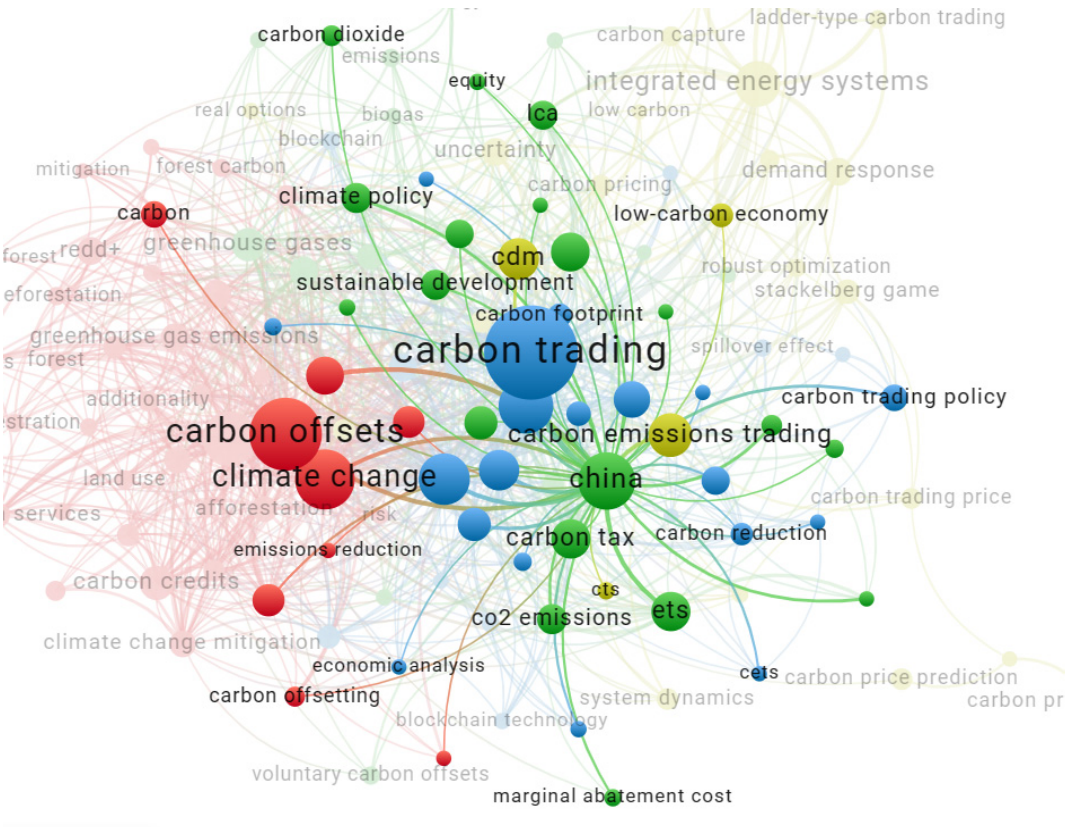


Figure 11. Relationship between cluster 2 keywords and other clusters.

Table 9. Top 11 terms in cluster 2.

Terms	Frequency	percentage
China	97	20.1
Biomass	54	11.2
Carbon tax	54	11.2
Personal carbon trading	54	11.2
Carbon trading	45	9.3
Carbon offsets	35	7.2
Climate policy	35	7.2
Sustainable development	31	6.4
Emission trading scheme	28	5.8
Bioenergy	27	5.6
Climate change	23	4.8
Total	483	100

Cluster 3 primarily entails strategies and policies in carbon markets for achieving carbon neutrality. This theme pertains to approaches and policies related to carbon trading and markets to reduce carbon emissions and achieve carbon neutrality across sectors and geographic levels. The keywords most frequently used are carbon trading, carbon markets, carbon emissions, and carbon neutrality. The keyword "carbon trading" appears 319 times, indicating extensive research in this field, encompassing various methods, outcomes, and perspectives related to carbon trading, as presented in Table 10. In this cluster, numerous researchers discuss the mechanisms and markets of carbon trading, focusing on the structure, regulation, and effectiveness of carbon trading markets, including ETS such as the EU ETS. Then, 5 top-cited papers on carbon trading were reviewed to analyze the findings of the researchers, as presented in Table 11.

Table 10. Top 11 terms in cluster 3.

Terms	Frequency	%
Carbon trading	319	37.4
Carbon emissions	122	14.3
Carbon neutrality	74	8.7
Carbon market	72	8.5
Carbon emission reduction	49	5.8
Carbon price	44	5.2
EU ETS	39	4.6
China	37	4.3
Personal carbon trading	37	4.3
Climate change	30	3.5
Integrated energy system	29	3.4
Total	852	100

Table 11. Top-cited papers on carbon trading.

Cited	Method	Important Findings	Contributions	Ref
270	- The Blockchain-enabled Reputation-Based Emission Trading Scheme (BCRB) leverages blockchain technology and incorporates a reputation system for participant trading	- BCRB can be deployed more quickly compared to other schemes requiring total modification.	- Propose an enhanced ETS scheme that leverages blockchain technology and smart devices to enhance ETS policy compliance metrics.	[1]
250	- Propensity Score Matching–Difference in Differences (PSM-DID method)-based empirical examination of the carbon trading system.	- Carbon trading schemes and the transition to a low-carbon economy in China are closely related.	- Research on how China's carbon trading scheme affects the advancement of a low-carbon economy.	[36]
207	- Two-region recursive dynamic CGE model	- An ETS could lower the cost of carbon reduction, impacting GDP at the macro level and sectoral output at the sectoral level.	- Assessed the effects of ETS on the economy in the province of Guangdong	[37]
174	- VAR model - DCC-TGARCH model - BEKK-GARCH model	Price fluctuations in the coal market tend to be mirrored in the carbon market, which transmits these fluctuations to the natural gas market. - Fluctuations in the Brent oil market does not significantly impact volatility in the carbon market. - Fossil energy markets and the carbon market tend to move in the same direction, exhibiting a positive correlation.	- Enabling emission trading installations to participate in the carbon market at a reasonable cost and helping investors manage investment risks and efficiently structure their portfolios.	[37]
149	- NN-based model: RBFNN - SVM-based models: PSO-SVM, SA-FFOA-SVM - Decision tree-based models: RF and XGBoost - Semi-empirical model: GWO-KNEA	- The upgraded RBFNN and enhanced GWO-KNEA models provide the best prediction performance across most carbon price and trading volume datasets.	- Offering sources to select future open carbon market trading models.	[38]

Cluster 4 pertains to the integration and optimization of energy systems for carbon management. This cluster contains integrated energy systems, carbon trading mechanisms, and strategies for achieving a low-carbon economy. The keywords most frequently used are integrated energy systems and carbon development mechanism (CDM). The top 11 terms in cluster 4 are presented in Table 12. The keyword integrated energy systems are closely related to other keywords such as energy efficiency, virtual power plant, power-to-gas, and hydrogen energy. These terms involve developing and optimizing integrated energy systems that enhance overall energy efficiency and incorporate innovative technologies such as virtual power plants and hydrogen energy solutions.

Table 12. Top 11 terms in cluster 4.

Terms	Frequency	Percentage
Integrated energy system	80	22.5
Carbon trading mechanism	50	14.0
Carbon emissions trading	35	9.8
Carbon trading	33	9.3
Uncertainty	31	8.7
Demand response	29	8.1
Integrated demand response	29	8.1
Stackelberg game	22	6.2
Low-carbon economy	17	4.8
Carbon accounting	15	4.2
Carbon price forecasting	15	4.2
Total	356	100

Moreover, carbon trading management, frequently linked with the CDM, employs market strategies to regulate pollution by offering financial rewards for decreasing pollutant emissions. The CDM, outlined in the Kyoto Protocol as one of the adaptable mechanisms, permits developed nations to fund emission reduction initiatives in developing nations as a component of their obligations to curb or diminish greenhouse gas emissions. CDM is related to carbon emissions trading, carbon pricing, ladder-type carbon trading, Carbon Trading Scheme (CTS), and carbon trading price, focusing on the structure, dynamics, and pricing within carbon markets.

To further explore research trends related to carbon trading, we analyzed articles indexed with additional relevant keywords, including emission trading system, carbon market, integrated energy system, carbon auction, and emission certificate. For this supplementary analysis, we aimed to uncover insights and trends that may not have emerged in the initial co-occurrence analysis. The analysis provided a more comprehensive understanding of how carbon trading mechanisms, integrated energy systems, and emission policies are addressed in current research, highlighting critical intersections and emerging areas of interest in the field.

Using the keywords “carbon trading” and “carbon offsets”, we found relevant studies by Shrivastava (2019) and Zhongxiang Zhang (2016). Shrivastava [39] underscores the feasibility of integrating carbon offset initiatives into airline ticketing systems with minimal impact on ticket prices. By enabling passengers to offset CO2 emissions during online bookings, Indian airlines can achieve significant carbon sequestration outcomes with only a marginal price increase of 1.00% to 1.07%. The findings revealed a promising willingness among passengers to contribute to carbon offsetting, demonstrating a viable pathway for airlines to align their services with global climate goals. The study illustrates a complementary relationship between carbon trading and carbon offset initiatives. While carbon trading focuses on market mechanisms to allocate emission allowances, carbon offsets provide an actionable method for individuals and businesses to directly mitigate emissions. In this context, airlines facilitate carbon offsets by empowering passengers to voluntarily invest in reforestation or similar projects, effectively integrating personal contributions into broader carbon trading and reduction strategies. This synergy enhances the overall effectiveness of carbon market mechanisms in addressing climate change.

China's experience with pilot carbon trading schemes demonstrates the value of regional experimentation in shaping a robust and comprehensive national emissions trading system (ETS). By enabling pilot regions the flexibility to tailor their programs while maintaining shared objectives, China has gleaned vital lessons on enforcement, compliance, and market design. These insights lay a strong foundation for the establishment of a unified national ETS capable of advancing the country's energy-saving and carbon-reduction goals while promoting market stability and fairness [33]. The study highlights that carbon trading and carbon offset mechanisms are complementary tools within China's evolving ETS framework. While carbon trading facilitates the allocation and exchange of emission allowances among entities, offsets expand the system's flexibility by enabling participants to achieve reductions through external projects such as renewable energy or reforestation. Integrating offsets into carbon trading pilots has provided a mechanism to address price uncertainty and incentivize broader participation. This integration not only enriches the functionality of carbon markets but also enhances the potential for achieving national carbon neutrality goals.

Using the keywords "carbon trading" and "emission trading system (ETS)", relevant studies were identified by Dinh Hoa Nguyen (2019) [40] and Kai Tang (2021) [41]. Dinh Hoa Nguyen [40] underscores the potential of carbon trading schemes to drive significant emission reductions, as illustrated by Japan's potential national implementation. By integrating renewable energy deployment with an optimization model, the study demonstrates that Japan could achieve substantial emission reductions of 34% to 42% at moderate carbon prices. This transition from isolated efforts to a unified national Emission Trading System (ETS) would enhance the scope and efficiency of carbon trading, aligning with international climate goals. Kai Tang [41] provides further evidence of the effectiveness of carbon trading schemes in reducing carbon intensity, focusing on China's pilot emission trading system (ETS). The study reveals that the ETS not only decreases carbon intensity but also facilitates structural economic shifts. These findings highlight the importance of expanding and refining national carbon markets to sustain and amplify these benefits. Similar to Japan, China's experience demonstrates the synergy between carbon trading and emission trading systems. The ETS provides the regulatory framework, while carbon trading serves as the operational mechanism enabling entities to trade emission allowances and drive emission reductions.

Using the keywords "carbon trading" and "carbon market", relevant studies were identified by Rebecca Pearse (2014) [42] and Boqiang Lin (2022) [43]. Rebecca Pearse [42] casts doubt on the efficacy of carbon markets in achieving significant climate goals. The author argues that these markets suffer from inefficiencies, weak governance, and limited impact on emission reductions. This critique underscores the limitations of carbon trading, the transactional mechanism enabling entities to exchange emission allowances, within a flawed carbon market infrastructure.

Boqiang Lin [43] provides empirical evidence supporting this critique, demonstrating that China's carbon trading policies, while effective in reducing emissions, are primarily driven by government intervention rather than market forces. This finding highlights the complex interplay between carbon trading and the carbon market. While carbon trading serves as the operational tool, the carbon market, including its regulatory framework, plays a crucial role in its effectiveness. In China's case, the success of carbon trading is largely attributed to strong policy interventions and regulatory oversight, suggesting that a well-designed and robust carbon market infrastructure is essential to harness the full potential of carbon trading as a climate mitigation tool.

Using the keywords "carbon trading" and "integrated energy system", relevant studies were identified by Peihong Yang (2023) [44] and Hongbin Sun (2023) [45]. Peihong Yang [44] found that integrating demand response (DR) and a ladder-type carbon trading mechanism into an energy system's scheduling can drive significant progress toward a low-carbon economy. By optimizing cooling, heating, and electricity loads with carbon capture technologies, the system reduces operational costs and carbon emissions. This integration highlights the synergy between carbon trading and the integrated energy system, where carbon trading addresses financial and environmental emissions goals, while the energy system optimizes multi-source energy management across electricity, heating, and cooling.

Hongbin Sun [45] further supports this idea by presenting a low-carbon economic model for a park-level integrated energy system (PIES) that combines demand response, carbon trading, and flexible load integration. By incorporating a ladder-type carbon trading mechanism and optimizing multi-energy sources—such as combined heat and power (CHP) generation, new energy sources, and flexible loads—the system achieves lower operational costs, better peak energy management, and reduced carbon emissions. This study demonstrates that carbon trading and energy integration work together to enhance economic and environmental efficiency, ensuring a more responsive and cost-effective system.

Yongli Wang [46] presents an optimized operation model for regional integrated energy systems connecting electricity, thermal, and natural gas networks. By using the ladder-type carbon trading mechanism and the Fruit Fly Optimization Algorithm, the system minimizes economic costs and optimizes energy flows across networks. The research shows that integrating carbon trading with an energy system reduces operational costs by 8.44% and environmental emissions by 15.03%. This integration further solidifies the relationship between carbon trading and the integrated energy system, where the market-driven carbon trading mechanism and energy optimization techniques collectively ensure cost efficiency, carbon reduction, and sustainable energy management.

The three studies highlight a strong synergy between carbon trading and integrated energy systems. Carbon trading provides a market-driven approach to emission reduction, while the integrated energy system optimizes energy consumption across multiple sources (electricity, heating, cooling, and natural gas). Combining these mechanisms with demand response and ladder-type carbon trading models ensures a cost-effective, sustainable, and low-carbon energy operation, balancing economic and environmental objectives efficiently across interconnected energy networks.

Using the keywords "carbon trading" and "carbon auction", relevant studies were identified by Shuyu Luo (2023) [47]. They found a clear link between carbon trading and carbon auctions by demonstrating how the Vickrey auction strategy can optimize the trading of Chinese Certified Emission Reductions (CCERs) generated by renewable energy systems. Carbon auctions, as an integral part of the trading mechanism, provide a competitive platform to value CCERs fairly, aligning economic incentives with carbon reduction goals. This synergistic relationship ensures a more efficient allocation of resources and fosters the active participation of renewable energy in the carbon trading market.

Using the keywords "carbon trading" and "emission certificate", relevant studies were identified by Peng Chen (2023) [48], Xiuyun Wang (2018) [49], and Liang Zhang (2023) [50]. Peng Chen [48] optimized microgrid cluster operations by introducing a joint trading mechanism for carbon emissions and green certificates. This integrated approach reduces costs, minimizes emissions, and promotes cooperation among microgrids. Carbon trading and green certificate trading work together to ensure accurate accounting of environmental attributes and efficient resource sharing.

Xiuyun Wang [49] incorporated carbon trading and green certificate trading costs into a multi-objective environmental economic dispatch model. This approach reduces pollutant emissions and addresses uncertainties associated with wind power integration. Carbon trading and green certificates provide a market-based mechanism to manage CO_2 emissions and incentivize the adoption of renewable energy.

Liang Zhang [50] integrated carbon trading and green certificate trading into a virtual power plant (VPP) dispatch model. This approach optimizes the VPP's net profit while balancing economic and environmental goals. Carbon trading and green certificates incentivize carbon reduction and renewable energy utilization, leading to a more sustainable and cost-effective energy system.

The three studies highlight carbon trading and green certificates are complementary mechanisms that can be integrated into energy systems to promote environmental sustainability and economic efficiency. By incentivizing low-carbon practices and recognizing the environmental benefits of renewable energy, these mechanisms drive the transition to a more sustainable energy future. Carbon trading has a close relationship with the energy system to reduce carbon emissions. Some changes in energy technology that can be applied to support carbon emission reduction include:

a) Energy savings on the demand side,
b) Increasing the efficiency of energy production equipment, and
c) Substitution of fossil fuels with various renewable energy sources and new energy with low-carbon emission [51].

Considering the economic value of carbon through the carbon trading mechanism and implementation of a carbon tax can accelerate the penetration of renewable energy use. In addition, the use of an energy system optimization model can be an effective tool for evaluating the potential for reducing carbon emissions. In practice, energy system management can optimize the use of renewable energy, thereby contributing to reducing carbon emissions and increasing sustainability [52,53]. Renewable energy projects integrated into the carbon trading scheme can also benefit through Certified Carbon Emission Reduction (CCER) trading. This mechanism has the potential to increase economic value through more strategic investment decision-making with the support of a better information system [54].

3.5. Global carbon trading trends in various countries

We employ a three-field plot visualization technique to answer RQ2 for the contribution of countries to carbon trading research. This visualization, generated using the Bibliometrix-Biblioshiny application, offers a multifaceted perspective on research activity. Figure 12 presents the three-field plot for the field of carbon trading. It helps identify the central countries with the most publications (represented in the central zone). Additionally, it displays the keywords or topics (on the right) associated with these highly contributing countries, along with the names of their affiliated institutions (on the left).

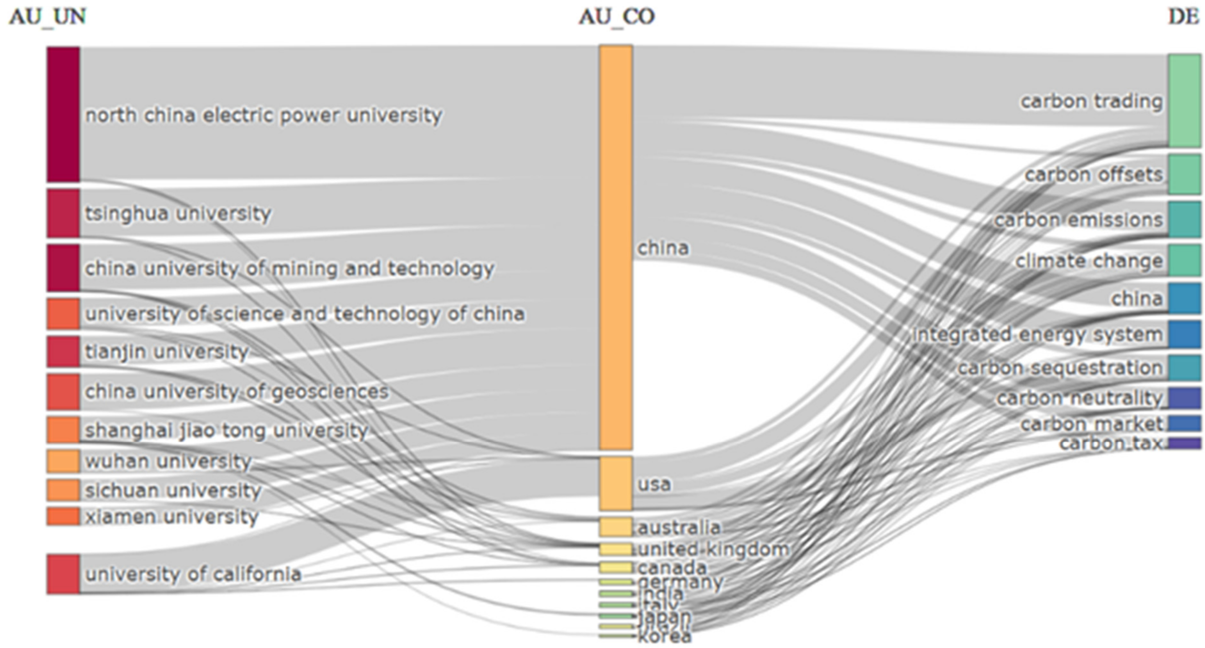


Figure 12. Three-field plot (Affiliations-Countries-Keywords (Topics)).

In Figure 10, the keyword "carbon trading" is utilized in most documents from 11 countries. Carbon trading is particularly significant for these 11 countries, with China leading in the number of research studies. This indicates that the central researchers and the country contributing the most to this field is China, which explores ten topics with keywords such as carbon trading, carbon offsets, carbon emissions, climate change, China, integrated energy system, carbon sequestration, carbon neutrality, carbon markets, and carbon tax. Researchers hail from 10 institutions, with North China Power University being the most productive, followed by Tsinghua University, China. Besides China, the United States and Australia also produce research on these ten topics, as detailed in Table 13.

Table 13. Top 11 countries based on ten research topics.

Country	Keywords									
	Carbon trading	Carbon offsets	Carbon emissions	Climate change	China	Integrated energy system	Carbon sequestration	Carbon neutrality	Carbon markets	Carbon tax
China	v	v	v	v	v	v	v	v	v	v
USA	v	v	v	v	v	v	v	v	v	v
Australia	v	v	v	v	v	v	v	v	v	v
United Kingdom	v	v	v	v	v	-	v	v	v	v
Canada	v	v	v	v	v	-	v	v	v	v
Germany	v	v	v	v	v	-	v	-	v	v
India	v	v	v	v	-	-	v	-	-	-
Italy	v	v	-	v	v	v	v	v	v	-
Japan	v	v	v	v	v	-	v	v	v	v
Brazil	v	v	v	v	-	-	v	-	v	v
Korea	v	v	v	v	v	-	v	-	v	v

Table 14. Six top-cited Chinese researchers' publication.

Cited	Research focus	Important findings	Suggestions	Ref
130	- The evolution of China's carbon emission trading programs (ETS). - Transition from regional to national carbon trading schemes.	- Educating entities is critical for active participation in carbon emissions trading. - Enforcing compliance requirements and classifying allowances as financial assets are vital. - National ETS policy is required to ensure the correct carbon trading operation. - The sector coverage and compliance standards differ in each pilot location.	- Educating covered entities, enforcing compliance rules, and defining valid allowances are crucial. - Implement uniform standards for measuring, reporting, and verification nationwide.	[33]
33	- Evaluating wood fuel sustainability and carbon-offset schemes in developing nations. - Comparing non-renewable biomass (NRB) estimations from carbon-offset initiatives with geographical wood fuel assessment.	- Emission reductions from wood fuel programs are estimated to be 41-59% more than expected. - Spatial study finds 'hotspots' for wood fuel in Africa and South Asia. - Clean-burning stoves have benefits that go beyond forest conservation and emission savings. - Recalibration of wood fuel programs may lower carbon revenues while increasing money.	- Reassess the mitigating potential of wood fuel projects for sustainability. - Use spatial assessment to identify places where interventions will be most successful.	[55]
28	- Work on China's carbon trading programs and market dynamics. - Investigation of pilot trading programs and compliance challenges in China.	- China's pilot carbon trading schemes differ in concept and implementation. - Market power problems are resolved in China's carbon trading project schemes.	- Establish a pricing ceiling and floor for efficient price uncertainty management. - Consider sectoral research to determine an appropriate carbon pricing floor. - Assess the necessity of maintaining a pricing floor in the future.	[56]
17	A barrier-topological feature-carbon offset (BTC)- -based model is being used to optimize ecological networks in karst environments. - Circuit theory, complex networks, and carbon offsets are used to optimize ecological networks.	- The BTC-based model optimized EN and identified restoration locations. - A case study in Guizhou Province revealed ecological progress and deterioration coexistence.	- Consider multi-objective optimization using spatial topological characteristics and carbon offset. - Adopt a BTC-based strategy for environmental restoration and achieving carbon neutrality.	[57]
15	Investigate the spatial and temporal patterns of carbon emissions and absorption across China to identify regional disparities and assess the efficacy of carbon compensation strategies.	- Different types of land have different abilities to absorb carbon, with woodlands and grasslands being the main carbon sinks. Construction and cultivated land are major sources of carbon emissions. Regional patterns in high and low-emission areas emphasize the importance of a holistic strategy for managing carbon at a regional level.	- Optimize land use structure for carbon sinks and efficiency, strengthen low-carbon awareness among citizens to reduce emissions, and implement interprovincial emission reduction policies to collaborate.	[58]
15	- Carbon neutrality in urban densification via precinct redevelopment and decarbonization planning. - Integrated carbon assessment methodology for calculating precinct carbon emissions.	- Urban regions' carbon emissions increase considerably with increasing populations. - Demographic changes can have a favorable influence on precinct carbon reduction. - Embodied carbon is an important component of the precinct's carbon signature.	- Expand energy-efficient buildings with 7.5-star ratings for redevelopment conditions. - Increase deployment of solar energy and rooftop PVs to reduce carbon emissions.	[59]

Table 13 illustrates the diversity of interest and scope of research across countries in global carbon trading and related environmental topics. Countries such as China, the United States, Australia, the United Kingdom, and Canada demonstrate comprehensive research engagement, covering a range of keywords from carbon trading to carbon tax. This indicates a strong institutional and academic focus on understanding and developing policies and technologies to reduce carbon emissions. Conversely, countries like Germany, India, Brazil, and Korea show gaps in integrated energy systems and carbon neutrality, highlighting potential opportunities for expanding research efforts. There is considerable global enthusiasm for carbon trading research, although the detail and breadth of this research differ among countries. Such differences underscore each nation's unique priorities and developmental stages in addressing climate change and carbon management.

Table 14 shows China's carbon trading research trend based on the six most cited articles. The research on China's carbon trading covers various studies, each providing valuable insights into developing, implementing, and optimizing the carbon emission trading scheme (ETS). In [33], the focus is on the development of carbon emissions trading schemes in China and the need to educate organizations on the significance of participating and adhering to these schemes. Zhang's research highlights the importance of strict enforcement of compliance rules and the precision of measurement, reporting, and verification processes for the success of these schemes. This fundamental study has played a crucial role in establishing the groundwork for future analyses and practical applications of ETS in China.

Expanding on this groundwork, the researchers in [33] thoroughly examine pilot carbon trading schemes, revealing notable differences in sector coverage and compliance requirements among regions. This study emphasizes the difficulties of incorporating regional ETS into a cohesive national framework. Customized strategies must successfully incorporate and align standards to accommodate the different variations. Zhang's findings highlight the intricate nature of establishing a unified national ETS and the significance of tackling regional inequalities to guarantee fairness and effectiveness.

Further developing the focus, the researchers in [55] delve into the carbon footprint of conventional wood fuels and uncover a tendency for wood fuel projects to overestimate emission reductions. This research emphasizes the wider significance of MRV processes within ETS, indicating that precise MRV is crucial for carbon trading and other projects to reduce emissions. The study highlights the importance of having practical expectations and strong verification processes to maintain the credibility and efficiency of emission reduction efforts.

Other researchers also examine optimization strategies that can enhance the effectiveness of carbon trading schemes. For instance, the researchers in [59] explore the correlation between urban densification and achieving carbon neutrality. They provide compelling case studies that highlight the substantial impact of urban planning in mitigating carbon emissions. Their research suggests significant reductions in urban carbon footprints that can be achieved by focusing on energy-efficient buildings and sustainable urbanization. The researchers in [58] explore optimizing land use for carbon sequestration, highlighting the importance of strategic land use planning in maximizing carbon sinks and achieving carbon neutrality objectives. In addition, the researchers in [59] employ multi-objective optimization models to enhance ecological networks, identifying crucial conservation and development areas to enhance ecological resilience. These studies emphasize the significance of incorporating different environmental strategies to enhance the efficiency of China's carbon trading schemes.

3.6. Carbon trading research in Indonesia

Indonesia is dedicated to reducing carbon emissions in alignment with the Enhanced Nationally Determined Contributions (NDC) for 2030, as stipulated in Law No. 16 of 2016 regarding the ratification of the Paris Agreement. Furthermore, the country is committed to achieving the Net Zero Emissions (NZE) target by 2060 [60]. Indonesia has initiated carbon trading in the electricity sector and is working to expand it to other sectors, in accordance with Presidential Regulation No. 98 of 2021, which addresses the economic value of carbon. Van den Bergh et al. argue that the most efficient combination is to integrate innovation support and information provision, either with carbon taxes and the implementation of subsidies or with carbon markets without the implementation of subsidies. Furthermore, they suggest that greater potential lies in harmonizing international policies, which will strengthen mitigation efforts over time [61]. The following are climate policy instruments that are active in Indonesia.

Table 15. Climate policy instruments that are active in Indonesia.

No	Policy	Policy focus
1	Law no. 11 of 2020	Concerning Job Creation, covers the legal basis for regulating carbon trading in Indonesia. Article 35 of this law stipulates that the government can establish carbon trading policies aimed at supporting emission reduction commitments.
2	Presidential Regulation No. 98 of 2021	Introducing the concept of Economic Value of Carbon (EVC) which includes carbon trading schemes, carbon taxes and other mechanisms aimed at reducing greenhouse gas (GHG) emissions.
3	Law Number 16 of 2016	Regulates the ratification of the Paris Agreement as a legal basis for Indonesia's commitment within the framework of climate change mitigation and adaptation.
4	Law Number 7 of 2021	Regulates carbon tax which is one of the important policies to tackle climate change in Indonesia. This policy aims not only to reduce greenhouse gas emissions, but also to encourage a shift to a more sustainable low-carbon economy.
5	Government Regulation Number 46 of 2017	Regulates Environmental Economic Instruments regulates economic instruments that can be used to support environmental protection and management efforts in Indonesia, including in the context of carbon trading.
6	Regulation of the Minister of Energy and Mineral Resources Number 22 of 2019	Regulating carbon trading mechanisms in the power generation sector in Indonesia. By implementing the Economic Value of Carbon (ECC) and the cap-and-trade system, the government seeks to reduce greenhouse gas emissions from the energy sector, while encouraging investment in low-emission technologies and renewable energy.
7	Regulation of the Minister of Environment and Forestry Number 21 of 2022	Regulates the Procedures for Implementing Carbon Economic Value (NEK) to achieve climate change control targets.
8	Regulation of the Minister of Energy and Mineral Resources Number 16 of 2022	Regulates the Procedures for Organizing the Economic Value of Carbon in the Electric Power Generation Sub-Sector, which is closely related to the implementation of carbon trading in the energy sector, especially electricity generation in Indonesia.
9	Financial Services Authority Regulation Number 14 of 2023	Providing clear guidelines for carbon trading and involving the financial sector, this regulation is expected to increase participation in efforts to reduce greenhouse gas emissions, as well as support Indonesia's commitment to addressing climate change.

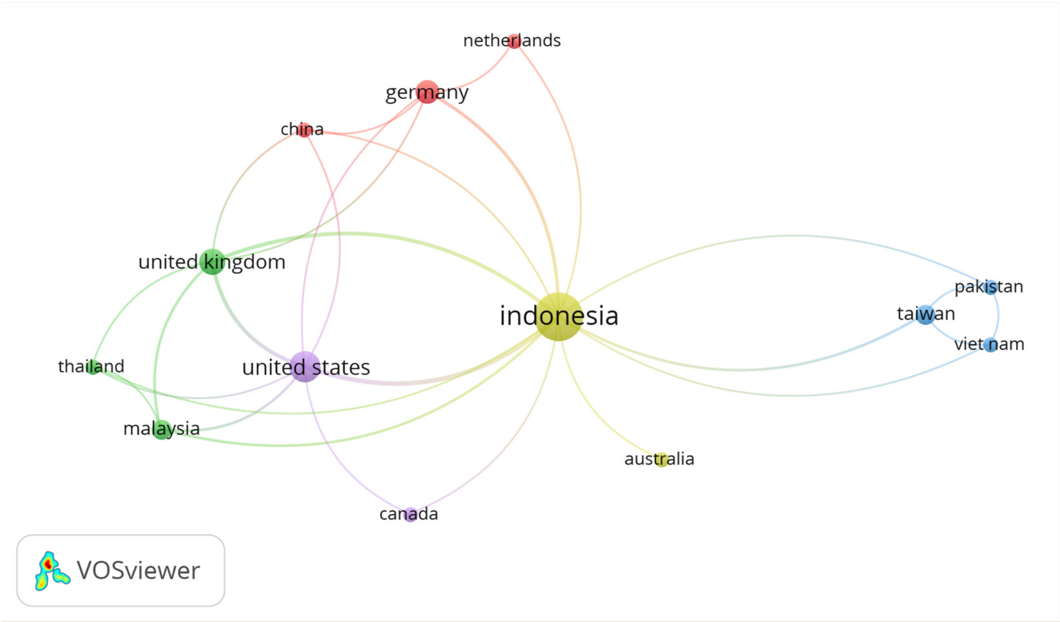
Indonesia's carbon market regulations provide a critical framework for GHG emission reduction and the achievement of national climate goals. The establishment of the Indonesia Carbon Exchange has led to heightened participation from corporations in carbon trading, reflecting growing public awareness and understanding of carbon markets and their role in combating climate change. Carbon market regulations have created opportunities for Indonesia to secure broader funding for climate change mitigation. The Carbon Economic Value (NEK) is expected to become a significant financial source supporting various environmental initiatives. However, further efforts are required to strengthen the market ecosystem, enhance stakeholder comprehension, and ensure integrity and transparency in carbon trading mechanisms.

We analyzed publication data to address RQ3 on Indonesia's contribution to carbon trading research. As shown in Table 16, Indonesia has authored 19 publications in this field. This number suggests significant potential for further research by Indonesian scholars. The most cited Indonesian publication (80 citations) originated from WWF-Indonesia and was co-authored by researchers from the Netherlands and Germany [62]. This study entailed planning hydrological restoration of Indonesian peatlands to mitigate CO_2 emissions. Specifically, it provided strategies for optimizing rewetting efforts through dam construction in Central Kalimantan. The methodology offers a detailed approach to peatland restoration with potential implications for the voluntary carbon market.

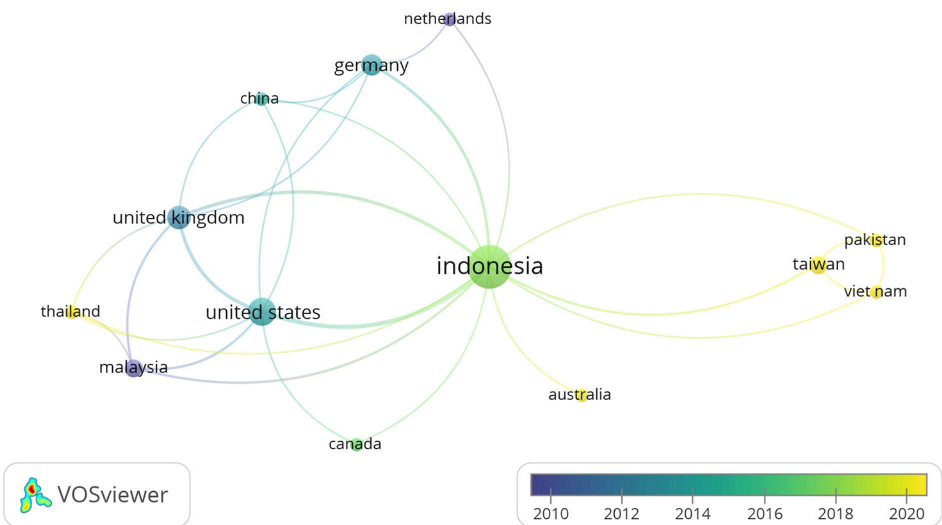
Table 16. Top-cited Indonesian researchers' publication.

Cited	Research Focus	Important Findings	Suggestions	Ref
80	A case study in the Sebangau catchment area in Central Kalimantan, creating an efficient and affordable method for restoring damaged tropical peatland hydrology	The drained peat swamp forest covering an area of 590 km^2 has been successfully rewetted, reducing annual emissions by 1.4 to 1.6 million tons of CO_2.	The active role of local communities will determine the success of restoration both in the planning and implementation stages.	[62]
48	Review transaction costs, power, and multi-level forest governance (REDD+ program)	Powerful organizations often dominate cross-level connections, although organizational similarity moderates this influence, which helps lower transaction costs.	Building cross-level relationships will be critical in creating an effective and fair multi-level governance system for REDD+ in Indonesia, allowing local organizations to address transaction cost issues.	[63]
44	Estimate the carbon payments needed to match the potential rubber revenue for local farmers by utilizing previously published spatially explicit rubber net present value (NPV) models from Yi et al. (2013).	Considering the conservation value of the carbon stores and the rich biodiversity in Xishuangbanna's natural forests, slightly reducing the rubber NPV would likely be less costly than trying to restore these resources.	• Rubber plantations should be restricted to established, productive lowland areas while protecting intact high-elevation forests and reforesting low-productivity plantations. • Carbon market prices must be significantly higher than they currently are to compete with rubber's profitability.	[64]
29	Review the Implementation of the RIL Guidelines in Sabah, Malaysia	Implementing the RIL guidelines reduced stand damage from 58% to 28% of the original stems and soil damage from 13% to 9% of the total area in RIL relative to CL areas.	An aerial system or hybrid system in which a bulldozer is combined with a skyline system could help reduce opportunity costs.	[65]
24	Estimate the extent to which carbon dioxide (CO_2) influences various applications of harvested wood products (HWP) and discuss the potential implications for measuring emission reductions within the framework of REDD+ in future global agreements post-2015.	Utilizing harvested timber directly for energy does not offset the depletion of carbon stored in forests. The significant factor in potential emission reductions primarily lies in logging residuals and displacement factors associated with various wood uses.	REDD+ observations and perceptions must encompass sustainable management and low-impact forest logging practices, including harvested wood.	[66]

Indonesian researchers have collaborated with 12 countries, with the most frequent collaborations occurring with the United States and Germany, as shown in Figure 12a. On average, Indonesian publications were released in 2017. The most recent collaboration was with Taiwan in 2022, as depicted in Figure 12b. For more detailed information, please refer to the online version.



(a)



(b)

Figure 13. (a) The network visualization of Indonesian collaboration, (b) Visualization of collaborative overlays in Indonesia.

Network visualization with co-word analysis on the co-occurrence analysis unit identified 81 keywords, with 54 exhibiting interconnectivity (Figure 14). "REDD+" emerged as the most frequent keyword, appearing six times and demonstrating a total link strength of 28. Notably, "carbon trading" appeared twice, once in a study by Dallydari (Widyatama University, Indonesia) and colleagues from Edith Cowan University, Australia [67].

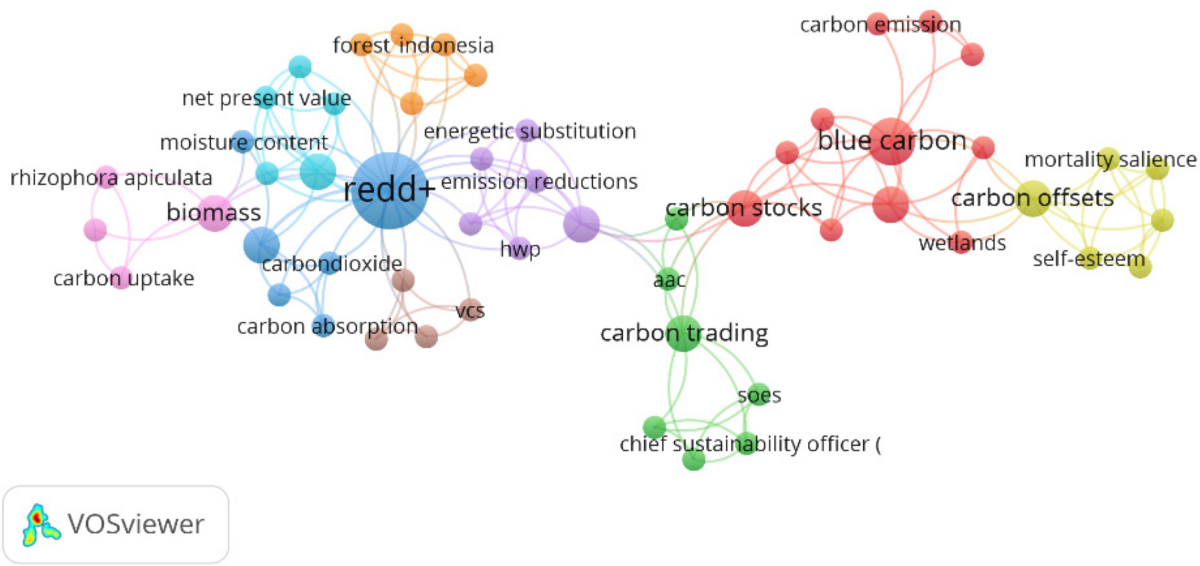


Figure 14. Network visualization of the author keywords in Indonesian publications.

The analysis result of Indonesian research showed two instances of the keyword "carbon offset," both originating from collaborations involving researchers from Sam Ratulangi University. We developpredictive models to optimize carbon offset programs within mangrove forest ecosystems [68]. Mangrove ecosystems hold significant carbon storage capacity and are commonly explored for forest carbon offset programs.

Figure 15 illustrates the yearly distribution of Indonesian carbon trading publications. The most recent study, published in 2023, investigated the critical role of the Chief Sustainability Officer (CSO) within multinational and state-owned enterprises (SOEs) in Indonesia [69]. This research, co-authored by researchers from Tarumanagara University, Jakarta, and Institut Teknologi dan Bisnis Ahmad Dahlan, Banten, highlights the importance of CSOs in promoting sustainability practices within Indonesian corporations.

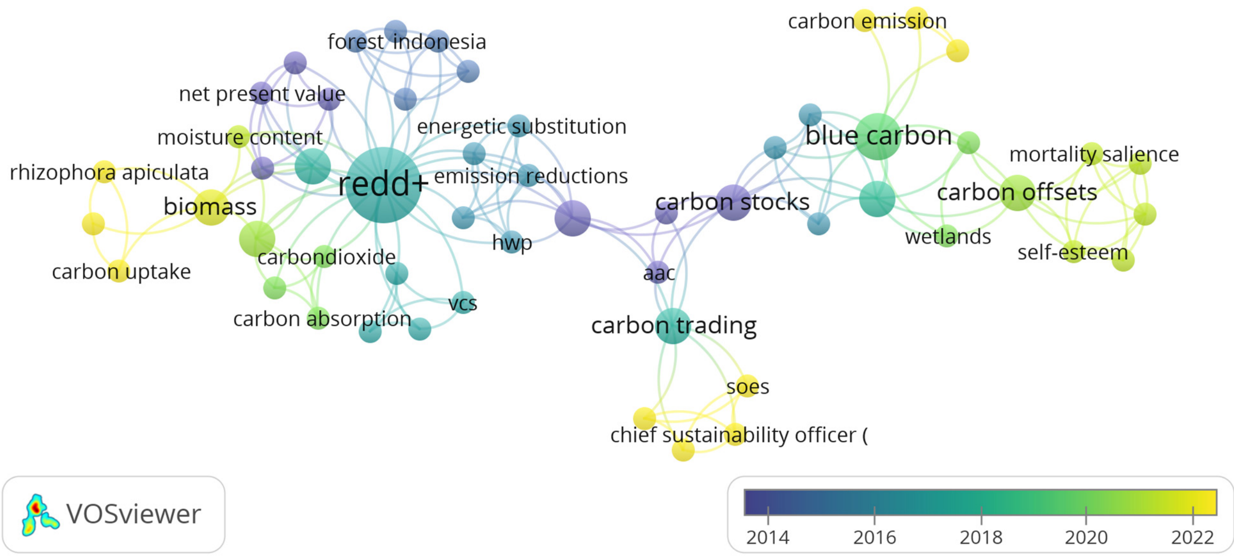


Figure 15. Overlay visualization of the author keywords in Indonesian publications.

3.7. Future research directions (Thematic evolution)

In this section, we address RQ 4 by identifying knowledge gaps in the current understanding of carbon trading and exploring promising areas for future research, as suggested by recent influential studies. Recent studies highlight emerging research frontiers in global and Indonesian carbon trading, pinpointing areas where further exploration could bridge knowledge gaps and drive advancements.

Research topics/themes in publications that are the subject of research continue to change, especially from newly published publications compared to older publications. The evolution of the topic is shown in Figure 15, which is divided into four periods. The data shows several widely used topics, as indicated by differences in size depending on the topic's use.

The left part shows several topics widely used in the first period, from 1993 to 2013. The second period is from 2014 to 2018, the third is from 2019 to 2022, and the right part shows the most recently used topics in 2023. Several topics appear throughout the period. This is an evolution of previously used topics and has connections in their content. For example, carbon trading emerged in 1993–2013 and evolved into 7 topics in 2014–2018: Bioenergy, carbon, carbon trading, climate change, deforestation, personal carbon trading, and REDD+.

For the 2019–2022 period, the research trend on carbon trading is divided into four topics: Carbon trading, China, climate change, and renewable energy. The latest period is 2023. The trend in carbon trading research is carbon sequestration and neutrality, but new topics, such as carbon trading policy, have emerged. This indicates that with so much research on carbon trading, policies are needed to regulate this matter.

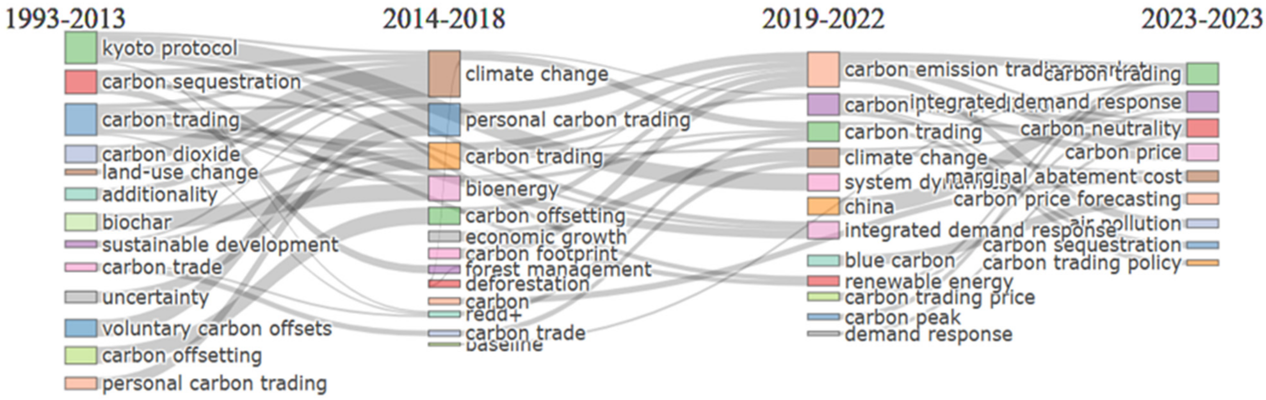


Figure 16. Thematic evolution biblioshiny (Parameter author keywords).

Table 17 displays many significant themes and recommendations for further studies based on the top ten referenced articles on CTP and related issues. Key issues include supply chain coordination, regional implications, market processes, information asymmetry, dynamic policy impacts, sector-specific analysis, and worldwide comparisons.

Table 17. Top-cited papers of carbon trading policy.

Ref	Year	Future research direction
[2]	2020	- Explore supply chain coordination with multiple competing members for enhancement. - Investigate dynamic models to address the static nature of the study.
[7]	2023	- Examine the effects of CTP on the low-carbon economy in various geographical areas. - Examine the contribution of technical advancement to a low-carbon economy. - Examine the implications for a low-carbon economy of improvements to the ecological environment.
[70]	2023	- Investigate market mechanisms and government interventions in carbon trading policies. - Examine how environmental laws affect innovation and economic progress.
[71]	2020	- Analyze asymmetrical information flow between government and enterprises for subsidies. - Investigate retailer's responsibility sharing and costs with manufacturers in supply chains.
[72]	2021	- Examine how dynamically changing land use is affected by carbon trading policies. - Incorporate other land types in the evaluation of carbon emission trading. - Consider internal variations in carbon trading schemes for the next studies.
[23]	2022	- Collect empirical data for market risk and firm size analysis.
[13]	2022	- Analyze emission policies' impact on industry structures in China. - Develop intertemporal dynamic CGE model for comprehensive policy support.
[73]	2023	- Investigate CETP's impact on GI in different industries and regions. - Explore the role of government intervention in promoting green innovation.
[74]	2023	- Examine the effect of local public spending on the power industry's efforts to reduce carbon emissions. - Examine how the carbon trading regime has affected emissions over the long run.
[75]	2023	- Study the impact of social factors on closed-loop supply chain. - Examine various forms of transportation with a range of carbon emissions.

A critical area for future research is fostering multi-level supply chain cooperation within a low-carbon framework. Thus, delineating the roles and interdependencies of diverse stakeholders, encompassing manufacturers and retailers, is paramount for identifying cost-sharing mechanisms and minimizing the trade-off between economic and environmental objectives [2,76]. Future investigations of supply chain carbon trading policies should encompass the impact of transportation modes, integrate the social dimension of closed-loop biofuel systems, compare the effectiveness of carbon trading with alternative policy instruments, and broaden sustainability assessments beyond carbon emissions [75].

Researchers should explore how urban and rural locations adapt to and benefit from this strategy, considering regional characteristics and various socio-economic aspects [7]. Additionally, research is needed to understand the interplay between market mechanisms and government intervention in the carbon trading industry. Thus, examining how different market-based solutions and regulatory approaches can complement each other to enhance Green Total Factor Productivity (GTFP) is crucial. This analysis should encompass the long-term economic and environmental sustainability of these mechanisms to inform the development of improved and adaptable policy frameworks [70].

A critical challenge within the low-carbon supply chain is the uneven distribution of knowledge among stakeholders [71]. Researchers should investigate how disparities in information availability and quality impact decision-making, efficiency, and overall supply chain performance. It is also vital to develop solutions to mitigate this knowledge imbalance. Furthermore, a more comprehensive evaluation of carbon trading policies' effects on land-use changes is necessary. This evaluation should encompass a wider range of land types, a deeper exploration of specific market complexities, and consideration of variations across policies. Additionally, research on developing and integrating low-carbon technologies for broader emission reductions should be promoted [72].

Furthermore, a comprehensive analysis of the impact of carbon emission reduction policies is essential [13]. Future studies could entail the effects and viability of extremely high carbon prices on inflation, consumer preferences, irrational behavior, and the wealthy [26]. Future analyses should encompass a broader range of economic factors and their interaction with different industries to address this gap. Intertemporal dynamic models are crucial for assessing these policies' long-term economic and environmental consequences. Additionally, incorporating penalty and rebate structures within policy design offers a promising avenue for further investigation. Finally, utilizing more comprehensive data sets is essential to analyze the distributional impacts across income levels and specific industry effects [23]. This proposed evaluating market risk and the impact of business size on liquidity to enhance future policy measures.

Investigating policy synergies for optimized emission reduction is crucial. A sector-specific approach to carbon trading legislation can reveal unique challenges and opportunities across industries, leading to more targeted and impactful policy recommendations. Researchers have explored the potential of carbon trading schemes for improving industrial sector efficiency in emission reduction [73]. These researchers aim to build on this knowledge by examining the influence of carbon trading policies on green innovation across industries and regions. Future study issues might include the influence of multinational corporations and the informal sector, the possibility of diverse carbon pricing between nations, and synergy with other tools [26]. Additionally, further research is needed to explore the impact of local public spending on carbon reduction within the power industry, along with the long-term effects of carbon trading policies on emissions [5].

A comprehensive examination of carbon trading programs across nations can offer valuable insights into their effectiveness and identify best practices for implementation. Comparative analysis, particularly between developed and developing countries, can reveal best practices that can be adapted for broader implementation [75]. This analysis should be complemented by examining global trends in technological innovation indicators, such as research and development (R&D) expenditure, total factor productivity, and patent filings. This will enable a more holistic assessment of how carbon trading programs influence and are influenced by green technology innovation globally [73]. Moreover, the differing significance of study subjects, such as comprehending the effects of carbon pricing across various nations and populations, may be essential. Future surveys should concentrate on specific areas of expertise within climate policy, since this targeted approach may produce more thorough and relevant information to inform following research endeavors [26].

In summary, forthcoming research on carbon trading policy should adopt a holistic approach that encompasses multiple facets of carbon trading. Supply chain analysis must examine inter-organizational collaboration, integrate social and environmental externalities, and evaluate carbon trading against alternative policy tools. Economic researchers must utilize rigorous approaches to evaluate intertemporal dynamics, market inefficiencies, and distributional implications. Mitigating knowledge disparities among stakeholders and assessing the ecological impacts of land-use alterations are essential. International collaboration, cross-national comparisons, and the incorporation of technical innovation measures are crucial for shaping global policy frameworks. Moreover, methodological developments, encompassing the use of high-quality data and the incorporation of multidisciplinary viewpoints, are essential for enhancing the understanding of the complex nature of carbon trading and formulating effective and fair climate policy. By investigating this prospective research avenue, researchers have the potential to significantly improve the development of more sustainable and effective carbon management systems, as well as to further understand the optimization of carbon trading policies to achieve economic and green goals.

4. Conclusions

In this study, we comprehensively analyzed carbon trading and offset research, focusing on global trends and Indonesia's role. The bibliometric results reveal a growing body of literature in the field, particularly dominated by contributions from China, the United States, and the European Union. Indonesia's engagement is increasing but remains limited in comparison, with 19 publications and collaborating with 12 countries over the past 30 years. Key themes include carbon management, innovations in sustainable energy policies, and integrated carbon trading mechanisms to achieve a low-carbon economy. In 2023, carbon pricing and carbon trading regulations emerged as key trends, playing a crucial role in the successful implementation of carbon trading at both national and global levels.

Despite providing valuable insights, re rely solely on Scopus-indexed publications, which may exclude relevant research from regional or less accessible databases. Future research should entail the effectiveness of carbon trading policies, particularly in developing countries, and explore the integration of carbon trading with broader environmental and economic strategies. Additionally, the role of technology, such as blockchain and AI, in enhancing monitoring and reporting systems and interdisciplinary studies addressing economic, environmental, and social dimensions are crucial for assessing the long-term sustainability of carbon trading mechanisms. Further exploration of public awareness and education's role in facilitating the successful implementation of carbon trading policies is also warranted.

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Conflict of interest

The authors declare that there are no conflicts of interest in the writing and publication of this work.

Use of AI tools declaration

While preparing this work, the authors used ChatGPT to improve language and readability. After employing this tool/service, the authors reviewed and revised the content as necessary and assumed full responsibility for the final publication.

Author contributions

Arief Heru Kuncoro: Conceptualization, Methodology, Validation, Supervision, Writing Original draft preparation. Afri Dwijatmiko: Methodology, Software, Data collection, Data Analysis, Writing Original draft preparation. Noer'aida: Methodology, Visualization, Data curation, Software,Writing—Original draft preparation. Vetri Nurliyanti: Data collection, Analysis, Writing—Original draft preparation. Agus Sugiyono: Data collection, Data Analysis, Writing—Reviewing and Editing. Widhiatmaka: Analysis, Writing Original draft preparation. Andri Subandriya: Conceptualization, Data collection, Validation. Nurry Widya Hesty: Methodology, Data Analysis, Writing Original draft preparation. Cuk Supriyadi Ali Nandar: Formal Analysis, Supervision, Writing—Reviewing and Editing. Irhan Febijanto: Formal Analysis, Investigating, Supervision, Writing—Reviewing and Editing. La Ode Muhammad Abdul Wahid: Validation, Formal Analysis, Supervision. Paul Butarbutar: Supervision, Writing—Reviewing and Editing. All authors reviewed the results and approved the final version of the manuscript.

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