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Original Research

Global Carbon Emission Reduction for Sustainable Development Research Hotspots and Frontiers – An Econometric Analysis Based on the Last 10 Years of WOS Literature

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Abstract

Carbon abatement research is dedicated to exploring and evaluating strategies and technologies to reduce atmospheric carbon dioxide concentrations to mitigate the effects of global climate change. Based on this, the article found through the econometric analysis of the core set of literature in the WOS database in the past 10 years that: firstly, carbon emission reduction research is in a period of development, forming a core journal with SCI TOTAL ENVIRON, Journal of Cleaner Production, etc., a core research team with Cai, Bofeng, Shan, Yuli, Dong, Feng, etc., and core countries with China, the United States, and the United Kingdom as the core issuing and research powers. Secondly, the five key areas of sustainable development, economic growth and consumption, energy efficiency, climate change, and energy consumption, and the three key areas of energy efficiency, climate change, and energy consumption, have been discussed in this study. Thirdly, there are five themes of sustainable development, economic growth and consumption, energy efficiency, climate change and drivers, and energy consumption. From these, nine research details, such as carbon emission measurement and monitoring, carbon emission reduction technology research, carbon emission reduction policy and management, energy efficiency, and clean energy development, carbon emission trading market, carbon emission efficiency and environmental policy research, data-driven economics and environmental analysis, climate change, carbon emission drivers, and so on are extended. Finally, the analysis of the evolutionary process has undergone three stages: exploration of basic theories, application of specific industries and policy interventions, and integration of carbon emission reduction targets into socio-economic development plans. Carbon emission and sustainable development research, carbon emission reduction, and energy efficiency improvement are the latest frontiers of carbon emission reduction research.

Keywords: carbon emission reduction, research hotspots, global perspective, bibliometrics

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Introduction

With the spread of industrialization and modern lifestyles, greenhouse gas (GHG) emissions from human activities have surged, posing unprecedented challenges to the global climate [1]. Carbon dioxide, as one of the most prominent greenhouse gases, contributes particularly to global warming [2]. It is widely recognized by the international community that effective measures to reduce carbon emissions are essential to mitigate the effects of climate change [3, 4]. To this end, governments, research institutions, and the business community are actively exploring strategies and technologies to achieve carbon reduction targets [5, 6]. Using data, environmental scientists try to simulate and predict the carbon cycle and its impact on the climate system by constructing complex mathematical models [7, 8]. Meanwhile, interdisciplinary research methods are widely used to explore the effects of low-carbon technologies and policies [9]. For example, researchers in the field of economics are exploring the long-term economic and environmental impacts of carbon taxes and emissions trading systems [10, 11], while experts in the field of engineering are working on the development of more efficient energy utilization technologies [12] to reduce carbon emissions from the industrial and transport sectors. In many research areas, researchers have been able to efficiently process and analyze huge literature datasets with the help of advanced scientometric tools such as CiteSpace and VOSviewer, revealing the connectivity between interdisciplinary studies and identifying the dynamic trends and knowledge structures of disciplinary developments [13, 14]. Through visualization techniques, researchers can identify key nodes of literature, explore current research hotspots and frontiers, and thus promote interdisciplinary dialogue and collaboration [15]. However, even though studies on carbon emission reduction have been published [16], systematic analyses of their bibliometric characteristics are still relatively insufficient. In the current urgent context of global climate change and carbon emission reduction, carbon emission research has been fruitful, covering a wide range of disciplinary areas, with far-reaching implications for future environmental policies and technological innovations. What are the main concerns of these studies? Which themes have become hotspots for academic research? How will future research develop? First, by sorting out the lineage, hotspots, and trends of carbon emission reduction research, we can better understand the development history of this field, thus promoting the enrichment, improvement, and soundness of the carbon emission reduction research system. This helps researchers grasp the overall framework of the research and provides strong support for subsequent academic research. Secondly, the innovative deployment and initiatives of the current carbon emission research can help review the progress of the global carbon emission reduction research promptly, innovate the research concepts, and clarify the future research direction. This is of great significance in guiding the innovation and development of the academic and practical communities in the field of carbon emission reduction. Finally, we can provide a practical reference for the global carbon emission reduction strategy in terms of the focus and future direction of the work. This means that we need to focus on the application of research results in practice and how to transform these results into concrete policy measures and technical means, to contribute to the cause of global carbon emission reduction. This paper adopts the bibliometric method to systematically analyze the global carbon emission reduction research results from three aspects, namely, research power, research theme, and frontier evolution, to reveal the inner connection and development dynamics, to point out the direction for environmental science research, and to promote carbon emission reduction research to a higher level and deeper level of development.

Research Methodology and Data

Research Tools and Methods

Bibliometrics is a quantitative analysis method, based on the quantity, quality, citations, and other statistics and analysis of academic literature. This method reveals the development of academic research dynamics, trends, academic impact, and other information [17]. This study mainly uses two visualization software, CiteSpace, and VOSviewer, to sort out and analyze the key literature, hot topics, and development trends of global carbon emission reduction and sustainable development, through which this study aims to depict the global research hotspots in the field of carbon emission reduction, the logic of thematic evolution, as well as the cutting-edge progress of the research content, to provide reference and guidance for the subsequent related research. This study aims to map out the global research hotspots, the logic of theme evolution, and the frontier progress of research content in the field of carbon emission reduction, providing reference and guidance for subsequent related research.

Data Sources and Sample Cleaning

The research literature originated from the Web of Science Core Collection and was searched using TS = (“reduce carbon emission” and “low carbon development” or “sustainable development” and “carbon emission”) as the search expression, and set the period from 2014 to 2023, the search yielded an initial literature of 1467 articles. As shown in Fig. 1, by following the PRISMA systematic literature review methodology [18, 19], the literature was manually screened and collated by this, and then manually screened for inclusion in the checked literature titles. A total of 1,246 kinds of literature that met the research criteria were finally screened. The data after checking and cleaning were imported into VOSviewer to draw the keyword clustering view, and Citespace was used for keyword timeline analysis.

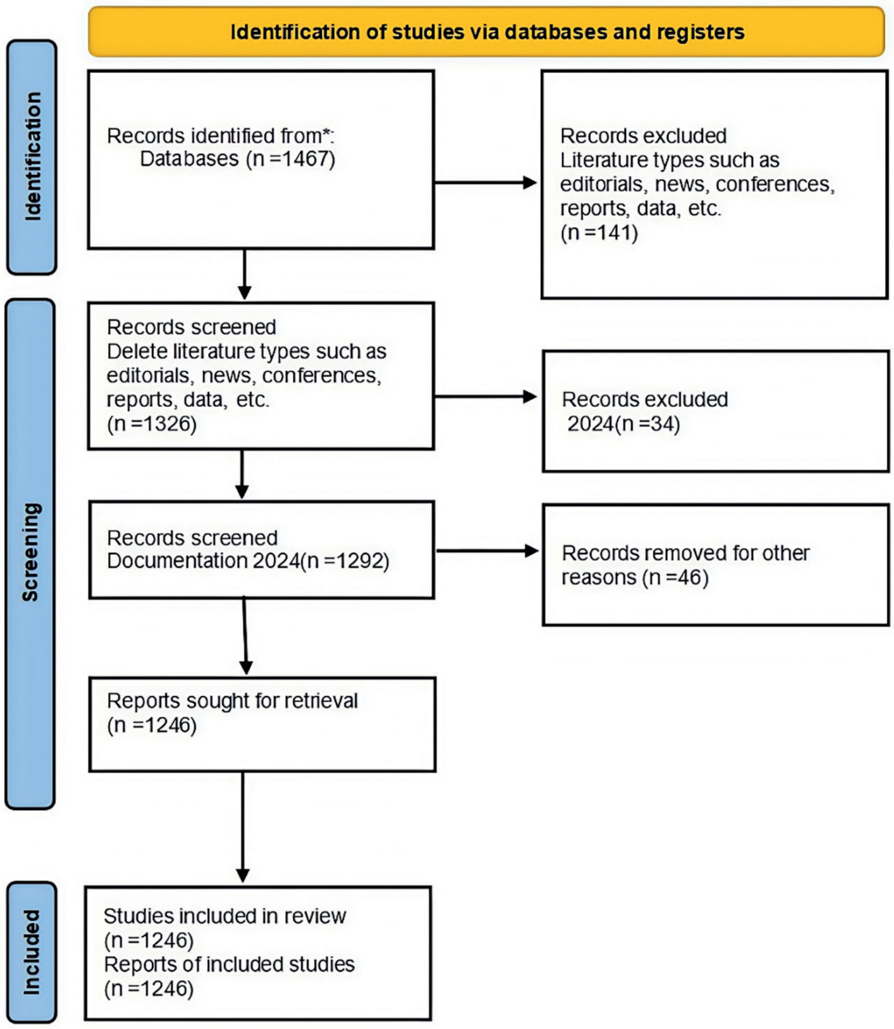

Fig. 1. PRISMA diagram.

Number of Publications and Research Capacity

Number of Communications

The number of publications is to reflect the activity of a research topic in a certain period. Through the study of the change in the number of publications, we can grasp the overall development stage and change trend of carbon emission reduction-related research. In this paper, through the statistics of the annual publication volume of carbon emission reduction from 2014 to 2023, it is found that the overall trend of the publication volume is upward as shown in Fig. 2. In 2014–2015, the publication volume was only 2 articles, and even though the research on carbon emission is continuing, it may not have formed enough social influence. Beginning in 2016, carbon emissions research began a sustained uptick, a growing trend that is closely linked to global developments in climate change policy. In 2015, the historic Paris Agreement was adopted globally, an international commitment that has significantly increased the sense of urgency for climate action, and related fields, including carbon emissions research, have been strengthened as a result. With the 2022 Green sustainable development and the common global pursuit of carbon neutrality, the number of publications and research activity in the field of carbon reduction will continue to grow steadily. This will further push the scientific and practical communities to make breakthroughs in combating climate change and building a green and sustainable society.

Issuing Journal

Journals not only have high academic influence but also play a key role in the recognition and dissemination of related research. According to the latest data, the statistics of the journals belonging to the sample literature are shown in Table 1: In the past 10 years, most of the carbon emission reduction research papers were published in energy and environment journals, especially the journals belonging to SCI TOTAL ENVIRON with high average citations, which are

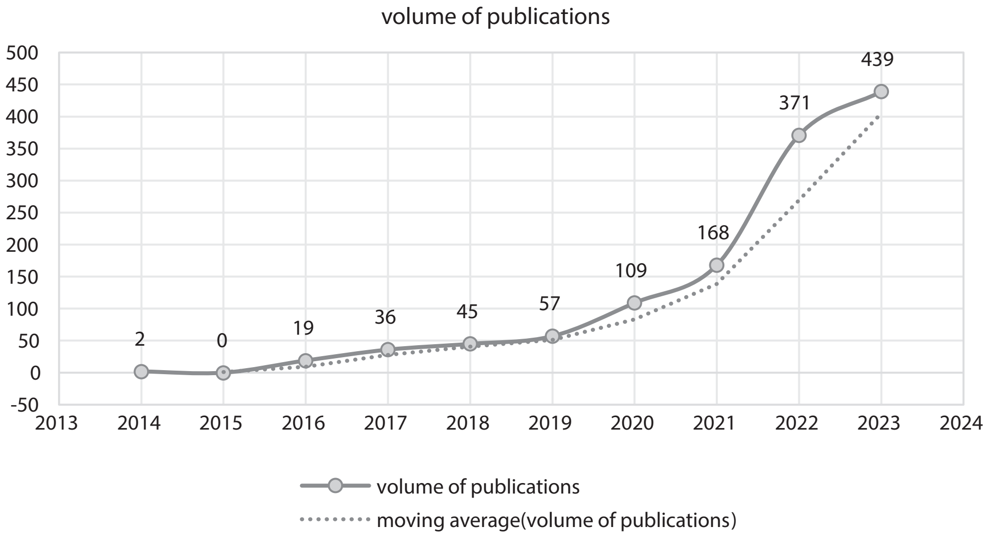

Fig. 2. Calendar Year Publications of Carbon Emission Reduction Research in the Last 10 Years.

Table 1. Top 10 core journals in terms of WoS publications.

Journal Name	if(2022)	Total Citation	frequent	centrality
SCI TOTAL ENVIRON	9.8	372,205	596	0.04
Journal of Cleaner Production	11.1	295,285	1061	0.06
Sustainability	3.9	187,953	614	0.02
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	15.9	168,341	677	0.02
APPLIED ENERGY	11.2	156,087	626	0.03
ENERGY	8.9	155,200	653	0.02
ENVIRON SCI POLLUT R	5.8	144,869	525	0.03
Journal of Environmental Management	8.7	99,689	509	0.03
ENERG POLICY	9	71,939	753	0.03
Energy Economics	12.8	42,372	531	0.04

all the top journals in the field of carbon emission reduction. This also indicates that carbon reduction research is mainly focused on energy and environment research. In addition, RENEWABLE & SUSTAINABLE ENERGY REVIEWS have an impact factor of 15.9, which plays an important role in promoting the research on low-carbon technologies and clean energy, and has received wide attention from the academic community, thus positively affecting the dissemination of knowledge and technological progress in the field of carbon emission reduction.

Research Strength: Core Countries and Teams

Country Distribution

To reveal the number of articles published by different countries in the field of carbon emission reduction research and the collaborative links between them, this study used a chord diagram to analyze the countries with the highest number of articles. As shown in Fig. 3, in terms of the number of published articles, Chinese articles ranked first, followed by the US and the UK, respectively. In terms of examining international cooperation, China has cooperated with major research countries in the field of carbon emission reduction, such as the UK and the US. This indicates that China's international academic exchanges in the field of carbon emission reduction research have been quite frequent, and the internationalization level of its academic research is high.

Research Team

Research teams and author clusters are key organizational forms that drive high-quality research. An in-depth analysis of the authorship clusters of carbon mitigation research is not only useful in revealing the research

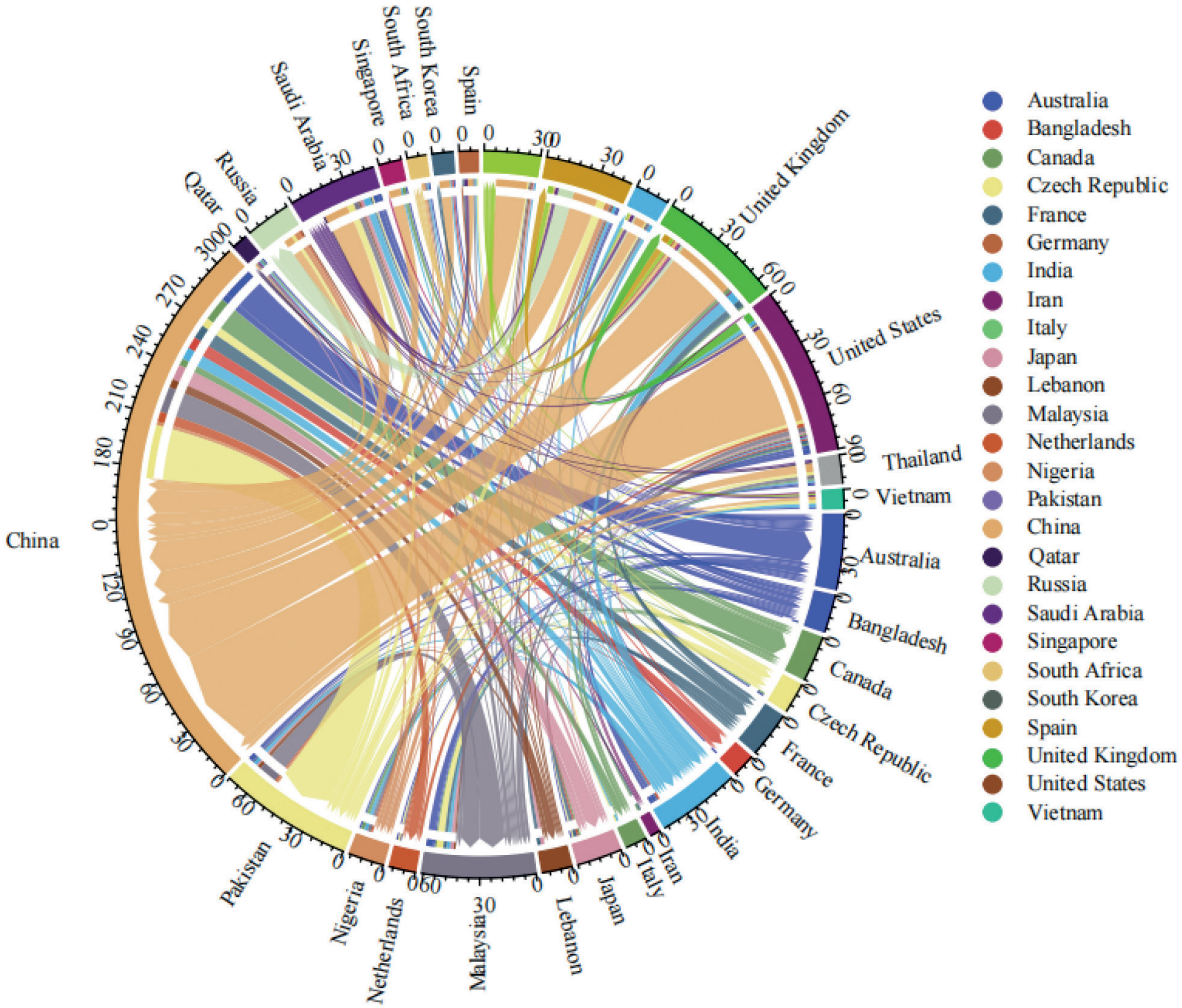

Fig. 3. Chord diagram of WoS literature in terms of country of affiliation and co-operation.

methodologies employed but also in identifying the current hot topics in scientific research. By combing through a sample of 1,246 papers, Price's Law states that about the average paper in any scientific field is written by a group of prolific authors, the number of which is approximately equal to the square root of the total number of authors. Specifically in the field of carbon emission reduction research, according to Price's law, the minimum number of publications by core authors in the field of carbon emission reduction research should be $m = 0.749 \times \approx 3$ (where max denotes the number of publications by the most prolific authors, and through the analysis of the Citespace data, Cai, Bofeng has become the most prolific scholar with the number of 16 publications, i.e., max = 16). Therefore, in the field of carbon emission reduction, scholars with no less than 3 publications can be regarded as core authors in this field. According to this criterion, a total of 88 scholars meet the criteria of core authors. Analyzing the cooperation of core authors, it is found that they roughly belong to three research teams:

First, the Cai, Bofeng research team, is mainly engaged in environmental and greenhouse gas emissions research. Urban greenhouse gases are a major source of climate change problems, and the establishment of the most disaggregated carbon accounting at the prefecture-level city level and a comprehensive analysis of the drivers of CO_2 emissions have helped to develop more effective mitigation measures [20–22]. During 2013–2023, his team continued research on changes in carbon emissions, using advanced data analysis and modeling techniques to more accurately quantify carbon emissions at different levels [23]. An integrated analytical framework was applied to customize carbon-neutral pathways from the full-domain perspective of greenhouse gas emissions [24]. The spatial and temporal changes in carbon emissions were sorted out [25], and the probabilistic

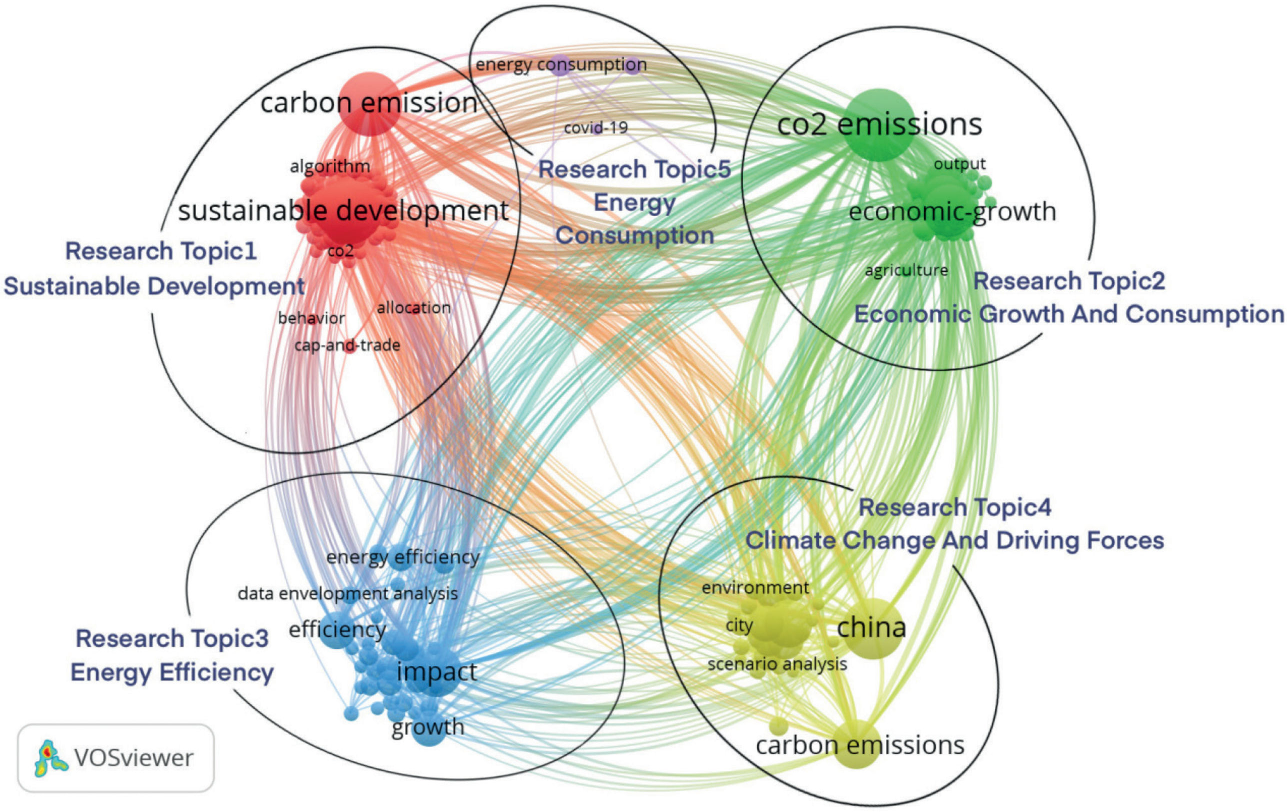

Fig. 4. Keyword clustering co-occurrence knowledge map.

method was used to track the urban evolutionary pattern and reveal the potential evolutionary pattern of urban CO2 emissions [26]. Through these in-depth studies, the Cai, Bofeng team provides a solid scientific foundation for climate action at the city level. They do not stop at analyzing and assessing and actively explore innovative ways to achieve carbon neutrality goals. In addition, the team has a reputation in the international academic community, and its research on carbon emissions and climate change has been widely cited for its positive impact on global climate governance.

Second, the Shan, Yuli research team, focuses on carbon emission accounting [27], regional sustainable development, and other research areas [28]. The team's work not only provides in-depth analyses and solutions to the environmental challenges facing the world but also includes constructing models to study carbon emissions [29] and examining the drivers behind carbon emissions [30]. The team conducted a systematic study of city-level carbon accounting, analyzing the process by which cities achieve peak carbon [31] and the drivers of carbon emissions in each type of city. Based on these findings, differentiated carbon emission reduction strategies for cities are proposed, aiming to achieve the goals of carbon peaking and carbon neutrality, which provide scientific support for the promotion of low-carbon and sustainable development of cities, and provide basic data support for the management practices of governments at all levels in the areas of carbon peaking and carbon neutrality.

Thirdly, Dong, Feng's research team has made progress in the field of carbon emission reduction. The team mainly explores the issues of carbon emission, environmental pollution, energy efficiency, and environmental regulation in emerging economies. Focusing on the synergistic decoupling of haze pollution and carbon emissions in emerging economies [32], as well as the evolution of carbon emissions and synergistic effects across industries [33], helps to advance the existing literature on synergistic emission reduction of environmental pollution, and deserves special attention from policymakers in emerging economies. In addition, the trends and reasons for decoupling CO2 and SO2 from economic growth were assessed for CO2 emission reduction and pollution abatement [34]. Through these studies, the Dong, Feng team provides valuable insights into the global understanding of the complexity and multidimensionality of carbon abatement, as well as a scientific basis for governments to formulate science-based carbon abatement policies and achieve the Sustainable Development Goals (SDGs).

Hot Topics in Research

Keywords are clear, concise, and specific descriptions of the core concepts of a particular topic. Keyword co-occurrence analysis is widely used to reveal the structure of the research field, the development trend, and the relationship between different topics. In this paper, we use

VOSviewer to cluster the keywords of 1246 sample documents and present a visual knowledge graph for the keywords with a frequency greater than or equal to 5. As shown in Fig. 4, research topic1 is sustainable development (red clustering), research topic2 is economic growth and consumption (green clustering), research topic3 is energy efficiency (clustered in blue), research topic4 is climate change and drivers (clustered in yellow), and research topic5 is energy consumption (clustered in purple). Afterward, the high-frequency keywords and link strengths of the five research topics were analyzed to more clearly depict the main content of different topic concerns, as shown in Table 2.

Sustainable Development

Sustainable development is a multidisciplinary concept, that mainly involves the environmental field, and its core objective is to improve the efficiency of resource use. Judging from the high-frequency keywords and link strengths involved in the current topic, current research mainly focuses on carbon reduction, carbon neutrality, carbon footprinting, carbon emissions, etc. Carbon emissions play a crucial role in the field of sustainable development and are closely related to global climate change, which will have a profound impact on the balance of ecosystems and the future of human society. By combing through the research, it is found that the research broadly includes three categories:

Carbon Emissions Measurement and Monitoring

Research in this area focuses on the development and refinement of methods used to quantify carbon emissions. This includes assessing the carbon footprints of different industries, regions, or products, as well as monitoring changes in atmospheric carbon dioxide concentrations. To gain a deeper understanding of the impact of global trade on carbon emissions, scholars [35] have studied the carbon footprint of global trade and improved the modeling of carbon emissions and trade issues. Scholars [36], who are also concerned with carbon emissions, used carbon emission statistics to propose optimizing the energy structure for green and sustainable development in response to the existing carbon emission dilemma. Accurate carbon measurements are the basis for developing effective mitigation strategies, providing policymakers with the necessary information to implement rational emission reduction measures.

Table 2. High-frequency keywords for hot topics of carbon emission reduction research.

Hot Topics	Number of nodes	High Frequency Keywords
Sustainable Development	81	algorithm, allocation, barriers, behavior, biomass, cap-and-trade, carbon, carbon emission, carbon emission reduction, carbon footprint, carbon neutrality, carbon tax, challenges, circular economy, climate, co2, competition, concrete, construction, coordination, cost, costs, decisions, demand, design, drivers, electricity, electricity-generation, emission reduction, emissions, energy, fly-ash, food security footprint, framework, generation, global warming, green, greenhouse-gas emission, impacts, integration, inventory, life cycle assessment, life-cycle assessment, machine learning, management, market, mechanism, mitigation, model, models, network, network design, optimization, performance, policies, power, reduction, resources, scenarios, selection, sequestration, simulation, storage, strategies, strategy, supply chain, supply chain manager sustainability, sustainable development, sustainable development goals, system, system dynamics, systems, technologies, technology, time, transport, uncertainty, waste, water
Economic growth and consumption	44	africa, agriculture, air-pollution, carbon-dioxide emissions, causality, co2 emissions, cointegration, consumption, countries, degradation, ecological footprint, economic development, economic growth, economic-growth, electricity consumption, empirical-evidence, energy use, environmental degradation, environmental kuznets curve, environmental sustainability, error-correction, fdi, financial development, foreign direct-investment, hypothesis, income, income inequality, international-trade, kuznets curve, nexus, nonrenewable energy, output, panel, panel-data, pollution haven hypothesis, regression, renewable energy, renewable energy consumption, renewable energy-consumption, technological innovation, time-series, trade, trade openness, unit-root
energy efficiency	33	carbon emission intensity, carbon emission performance, data envelopment analysis, dea, determinants, dynamics, economy, efficiency, empirical-analysis, energy efficiency, environmental regulation, environmental-regulation, green finance, green innovation, green technology innovation, growth, impact, index, industry, innovation, intensity, investment, perspective, policy pollution productivity, productivity growth, progress, quality, research-and-development, sector, slacks-based measure
Climate change and drivers	26	carbon emissions, china, cities, city, climate change, climate-change, decomposition, decomposition analysis, dioxide emissions, driving factors, driving forces, energy-consumption, environment, evolution, expansion, indicators, inequality, influencing factors, influencing factors, level, lmdi, low-carbon development, population, scenario analysis, stirpat model, urban, urbanization
Energy consumption	3	co2 emission, covid-19, energy consumption

Technical Studies on Carbon Emission Reduction

These studies have explored the effectiveness and feasibility of various carbon emission reduction technologies, aiming to provide sustainable development solutions for the global response to climate change. Scholars [37] proposed an ATC calculation method that minimizes unit carbon emissions and fuel costs by taking into account safety, economic, and environmental factors. Through this method, regional resources can be rationally allocated and the energy transfer capacity of existing equipment can be maximized. The proposal is not only in line with global carbon reduction targets but also supports a sustainable energy strategy.

Research on Carbon Emission Reduction Policy and Management

Within the field of carbon emission reduction policy and management research, scholars have focused on the development and implementation of effective carbon emission reduction strategies and corresponding management and regulatory mechanisms. To enhance the transparency and reliability of carbon emission rights trading, scholars [38] measured the quantification and monitoring of carbon emission rights through the application of blockchain technology; meanwhile, in the face of the challenges of peak carbon emissions and carbon neutral targets, scholars [39] proposed a multi-dimensional comprehensive evaluation system based on the integrated energy system of ports, which constructs three key aspects of energy efficiency, economy and environmental impact of the actual port energy system assessment indicators. These studies provide powerful tools and frameworks for global carbon emission reduction policymaking and management practices, ensuring the scientific and systematic nature of carbon emission reduction measures.

Economic Growth and Consumption

Globally, one of the core objectives of achieving sustainable development is to control and reduce carbon emissions. This goal is closely linked to energy consumption patterns and economic growth, and the interaction between the three is critical. As the issue of climate change, fueled by carbon emissions, becomes more pronounced, states and businesses are actively exploring effective ways to reduce greenhouse gas emissions, mitigate the trend of global warming, and alleviate its adverse environmental and social impacts. Achieving such a shift requires not only a profound reform of traditional energy production and consumption patterns but also a comprehensive restructuring of the global economy. These efforts can lead to a move towards a low-carbon economy that promotes environmental sustainability while opening up new pathways for economic growth.

Energy Efficiency and Clean Energy Development

To effectively reduce carbon emissions, the key lies in upgrading energy efficiency, advancing the development and application of clean energy technologies, and increasing the share of renewable energy in the overall energy mix. These measures not only reduce dependence on fossil fuels but also help to enable the development of new areas of economic growth, such as the green energy industry and the market for energy-efficient technologies. Scholars [24] used techno-economic analyses to explore in depth the interactions between climate change, energy resources, and sustainable development from a green economy perspective. In contrast, scholars [25] constructed an integrated optimization framework by combining a global climate model, multiple linear regression, and interval parameter planning, from which an energy-climate-water nexus model for China was established. In addition, based on the consideration of economic, social, and environmental sustainability, scholars [26] also constructed an optimal model for low-carbon city clusters. By implementing these strategies, we can realize economic growth while reducing total energy consumption, thus achieving the goal of a low-carbon economy.

Carbon Emissions Trading Market

Globally, to further incentivize emissions reductions and to meet carbon reduction targets, many countries and regions have established or are considering the establishment of carbon emissions trading markets. These markets create an economic incentive aimed at reducing greenhouse gas emissions by setting aggregate limits on emitted carbon and allowing the trading of emission allowances. Scholars [40] analyzed the carbon emissions trading system launched in 2017 from the perspective of market-based environmental regulation policies and identified areas for improvement. Scholar [41] further examines the impact of corporate participation in CDM initiatives on shareholder value and how corporate carbon trading affects corporate financial performance in the context of emerging countries. These studies provide valuable references for the design and improvement of the global carbon market and help to build a more efficient, fair, and resilient global carbon emissions trading system, which can effectively contribute to the realization of global carbon reduction goals.

Energy Efficiency

With the growing global awareness of climate change, governments, businesses, and all sectors of society are seeking effective ways to reduce greenhouse gas emissions by improving energy efficiency. Improving energy efficiency involves not only innovations at the technological level, such as more efficient production equipment, energy-saving building materials, and low-carbon transport modes but also requires changes at the behavioral level, such as optimizing energy consumption patterns and increasing public awareness of energy conservation. In addition, to facilitate this process, policymakers are implementing a range of incentives, including tax incentives, subsidies, and energy efficiency standards, to encourage industry transformation and consumer choice of more energy-efficient products and solutions. Research has shown that there is a significant positive correlation between energy efficiency and carbon reduction and that by implementing comprehensive energy efficiency strategies across multiple sectors, energy demand and greenhouse gas emissions can be significantly reduced, thereby combating climate change and facilitating the transition to a green and low-carbon economy.

Study on Carbon Emission Efficiency and Environmental Policy

To explore how to quantify and improve the carbon emission efficiency of energy use and assess the carbon emission intensity and performance of different economic sectors and regions. Scholars [42] establish a comprehensive set of indicators to explore the spatial spillover path of urban carbon emission efficiency in order to reflect the evolutionary characteristics of carbon emission efficiency and its spatial clustering effect. The impact of the formulation and enforcement of environmental regulations on the emission reduction effect and the role of environmental monitoring in pollution control are analyzed. On this basis, scholars [43] emphasize the importance of scientifically assessing carbon emission efficiency to safeguard the sustainable development of key infrastructures, such as sewage treatment plants. These research results provide important references for optimizing environmental policies, improving pollution control, and promoting the development of a low-carbon economy.

Data-Driven Economic and Environmental Analyses

In the field of data-driven economic and environmental analyses, advanced data analytics methods, such as packet analyses and data mining techniques, are applied to assess and improve carbon emission efficiency and develop performance gap-based metrics. By drawing on economic principles and methods, these studies provide insights into energy efficiency, pollution control measures, and the economic impacts of carbon reduction policies. Specifically, scholars [44] applied data envelopment analysis techniques to construct an energy congestion model to assess the carbon emission reduction effect of the coal-fired power generation sector, which provided a valuable reference for regional energy efficiency optimization. On the other hand, scholars [45] innovatively developed a comprehensive indicator that integrates multiple dimensions such as energy, environment, economy, and resources to measure the performance of economic development under the consideration of carbon emissions, thus providing a new quantitative tool for sustainable economic growth in a carbon-conscious economy. These research results not only promote a deeper understanding of the interaction between the economy and the environment but also provide policymakers with scientific data to support the formulation of more effective environmental policies and economic development strategies.

Climate Change and Drivers

This research area focuses on analyzing and managing carbon emissions in relation to climate change. The core themes of the research include exploring the drivers of carbon dioxide emissions, understanding the impacts of environmental evolution on the climate system, and assessing how the various drivers are shaping global and regional climate change trends. Overall, these areas aim to deepen the understanding of the complex relationship between carbon emissions and climate change, and to explore effective environmental management strategies to address the challenges posed by climate change for the sustainability of the environment and the development of human societies.

Climate Change

There is a strong link between climate change and carbon emissions, with carbon dioxide (CO2) emissions being one of the major contributors to global warming and climate change. These greenhouse gases mainly come from the burning of fossil fuels, industrial production activities, deforestation, and other human activities. In response to this global problem, scholars [46] used a model to analyze carbon emissions and energy consumption in China's construction industry and explored the interrelationships and dynamics between these variables and GDP growth as well as carbon emission intensity. The findings not only provide a scientific basis for carbon emission reduction in the construction industry but also provide valuable data support for the development of targeted emission policies for the industry. These efforts have important practical significance and policy guidance value for understanding and responding to the challenges of climate change.

Analysis of Carbon Emission Drivers

In the analysis of carbon emission drivers, research efforts have focused on exploring how core elements such as economic growth, industrial and energy structure, population size, technological progress, and fixed asset investment affect carbon emissions, an analytical process that not only aims to gain a deeper understanding of the interaction mechanisms of these drivers but also strives to identify potential opportunities for emission reductions. In particular, the study by scholar [47] focuses on analyzing the intrinsic dynamics of carbon emission efficiency in China's construction industry and reveals the key influencing factors within the industry. Through such analyses, strong data support can be obtained for the government and enterprises to formulate and implement effective environmental policies and carbon emission reduction strategies to meet the challenges posed by climate change and to facilitate the green transformation of the economy.

Energy Consumption

The new crown epidemic has led to embargo measures and economic slowdowns around the world, which in turn have triggered significant declines in energy consumption and carbon dioxide emissions. This impact has provided a degree of environmental "respite" in the short term, but the long-term impact will depend on the path of economic recovery from the epidemic and the climate policies adopted by countries. As the economy gradually recovers, there is a need to be vigilant about a possible upward trend in energy consumption and emissions, while strengthening policy guidance and technological innovation to promote the development of green energy and low-carbon technologies to ensure sustainable and environmentally friendly growth.

Evolution of the Frontiers of Research

The evolution of the frontiers of global carbon emission reduction research is a complex process involving multiple factors, including historical data analysis, research methodology evolution, observation of international trends, action patterns of different countries, assessment of the current situation, and future outlook. Comprehensive analyses of these dimensions can provide a more comprehensive understanding of the dynamics and challenges of global carbon emission reduction and support the formulation of effective emission reduction strategies.

Frontier Evolution Logic

This study uses CiteSpace to analyze the evolution of high-frequency keywords in time zones of 1246 target literature to track and observe the dynamic development process and cutting-edge themes of the whole research history, as shown in Fig. 5. From the distribution of keywords and their relationship sparseness, it can be seen more clearly that the global carbon emission reduction research has certain stage characteristics, which are roughly divided into three phases: the keywords are more independent of each other in 2014–2016, which is the 1st phase (germination); the keywords are more refined and their relationship is gradually tightened in 2017–2019, which is the 2nd phase (exploratory); and the new terminology in 2020–2023 is further derivation and development, phase 3 (development).

Phase I: Emergence (2014–2016)

Firstly, the keywords in this stage are relatively sparse, belonging to the early stage of carbon emission reduction-related research, and the keywords describing the sustainable development of carbon emission reduction are mostly large-grained basic concepts, for example, “climate change”, “CO2 emissions”, “country”, “model” and so on. These keywords represent the fundamental issues of research related to carbon emission reduction, which clarifies that at this stage, the research mainly focuses on the basic situation of climate change and CO2 emissions, and is discussed and researched according to the situation of different countries. It is found that there is heterogeneity between carbon emissions and countries at different levels of development, and for developed countries, the level of technology is an important factor affecting carbon emissions. For developing countries, population size is a potentially important driver of carbon emissions [48].

Secondly, due to the increasingly serious global environmental and climate crisis, and with the gradual maturity of the carbon emissions trading system in various countries, carbon emission reduction-related research began to appear. In this period, scholars mainly constructed models to generate indicators to measure carbon emissions and to study the basic response mode of countries to climate change. The “model” in the figure also means that the scientific method of constructing models to predict and evaluate carbon emissions is taking shape. For example, based on the theory of life cycle assessment, the construction of a life cycle quantitative model for carbon emission measurement [49]; through the establishment of a sensitivity model, the greenhouse gas effect and climate change were successfully combined and found that: China’s per capita GDP income and population growth are the most important drivers of carbon emissions; at the same time, as the world’s largest developing country, China’s urbanization is also an important factor that affects its carbon emissions [50].

Finally, there are studies in this phase about the specific utility brought by carbon emission reduction, and a few studies believe that reducing carbon emissions will hurt economic development in the short term, and can accelerate the development of renewable energy in the long term. From the content of the main concepts of this stage in the time zone map, the meaning and its involvement in the literature found that this stage of the research is mainly on the impact factors of carbon emissions research and discussion, but for the ways to limit carbon emissions and carbon emission reduction and economic synergistic development of the program did not carry out in-depth research. Therefore, the basic research at this stage lays the foundation for subsequent extended research on the sustainable development of carbon emission reduction.

Stage 2: Development Stage (2017–2019)

From the characteristics and evolution of keywords in this stage, it can be found that: first, in this interval, the scale of keywords shows explosive growth compared with the previous stage, while becoming more concentrated and obvious. This indicates that carbon emission reduction-related research is beginning to mature, with more diverse research topics and key concepts being refined. Secondly, we can see that the keywords “energy consumption”, “efficiency”, “economic growth”, “economic development”, and so on, “economic development” and other keywords are more prominent in the figure, which shows that the research began to pay attention to the relationship between energy consumption and economic growth and analyze the balance between economic growth and energy consumption, to provide a scientific basis for carbon emission reduction. For example, by analyzing China’s provincial panel data, it is found that economic output (EO) and energy intensity (EI) are the main inhibitory and promotional factors of carbon emission reduction, respectively [51].

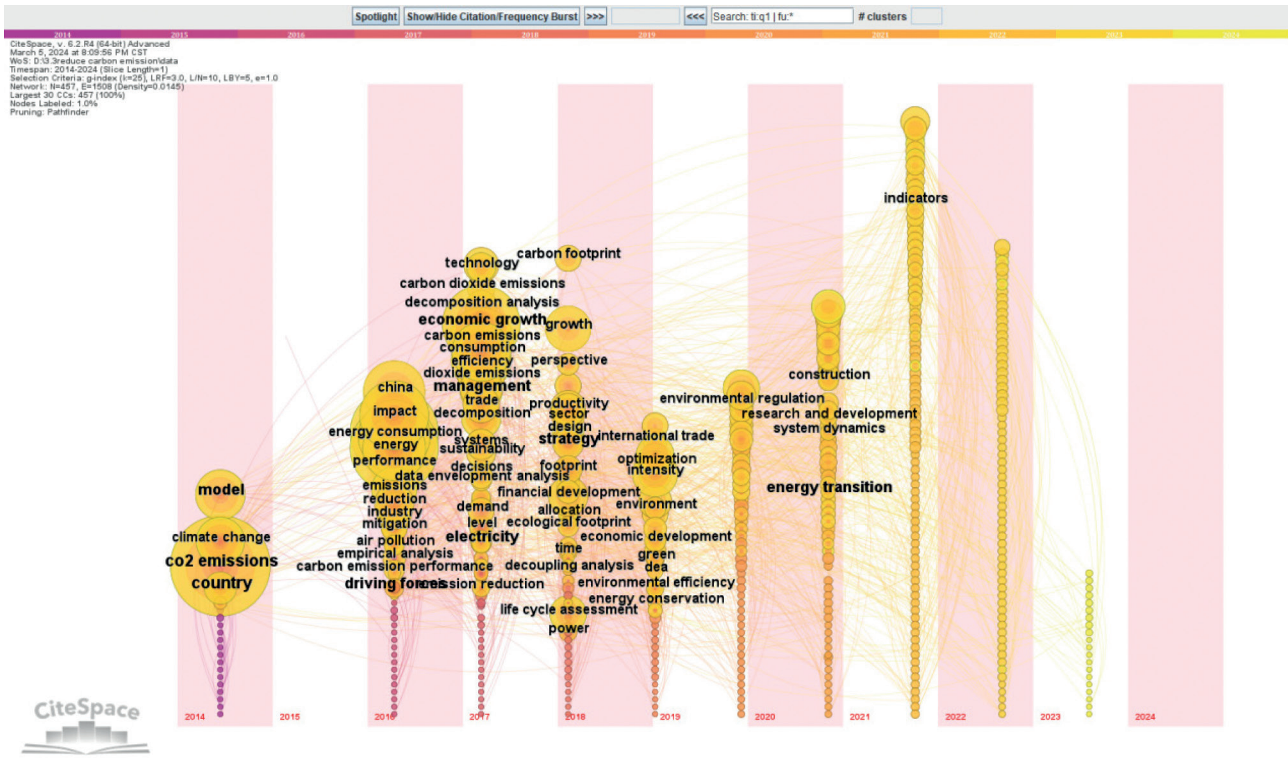

Fig. 5. Keyword evolution time zone map.

Thirdly, carbon emission reduction has been gradually extended to more and more different fields, such as industrial production, transport, urban planning, and so on. Related empirical studies have emerged, focusing on the moderating and cross-effects of important indicators for measuring economic development on the relationship between carbon emission reduction and the secondary industry, and it can be seen that the focus of the research has been shifted to how to achieve the transformation of the energy structure through a systematic approach, emphasizing the importance of technological innovation and industrial transformation and upgrading. For example, technological progress is a central force in promoting income growth and reducing carbon emissions [52]; carbon emissions rise with the growth of per capita GDP while at the same time having a smaller long-term impact on the industrial index. Fourth, carbon emission reduction and sustainable development strategies have established closer links with specific policy measures, such as the rise of concepts such as the development of clean energy [53], the promotion of green buildings [54], and transport systems [55]. In addition, research on the net effect of carbon emission reduction policy implementation is gradually emerging, finding that governments can promote investment in corporate technological innovation and green energy equipment upgrading by levying carbon emission taxes and subsidizing carbon emission reduction policies [56]. From the content of the key concepts in this phase in the time zone map, their meanings, and the literature they relate to, it is found that the keywords in this phase reflect the fact that the research focuses more on the actual abatement strategies and measures and how they are integrated into the larger socio-economic system. In addition, carbon reduction and sustainable development strategies are closely linked to practice and are gradually integrated into policy formulation and implementation, and can be seen as key drivers of change in environmental protection and sustainable development paradigms.

Phase 3: Expansion Phase (2020–2023)

From the characteristics and evolution of keywords in this phase, it can be found that, firstly, the nodes of keywords in this phase are significantly larger, indicating that these keywords appear more frequently in the research literature during this period. In particular, the significant growth of the keyword "indicators" in 2021 suggests that researchers are looking for and developing new indicators that can quantitatively assess the process of sustainable development and carbon reduction [57]. These indicators may be used to monitor the effectiveness of policies, the assessment of the environmental impacts of economic development models, and the achievement of international emission reduction targets. Secondly, the focus of research on carbon emission reduction and sustainable development has shifted to focus more on achieving a balance between long-term environmental goals and socio-economic benefits, such as exploring the bidirectional causal relationship

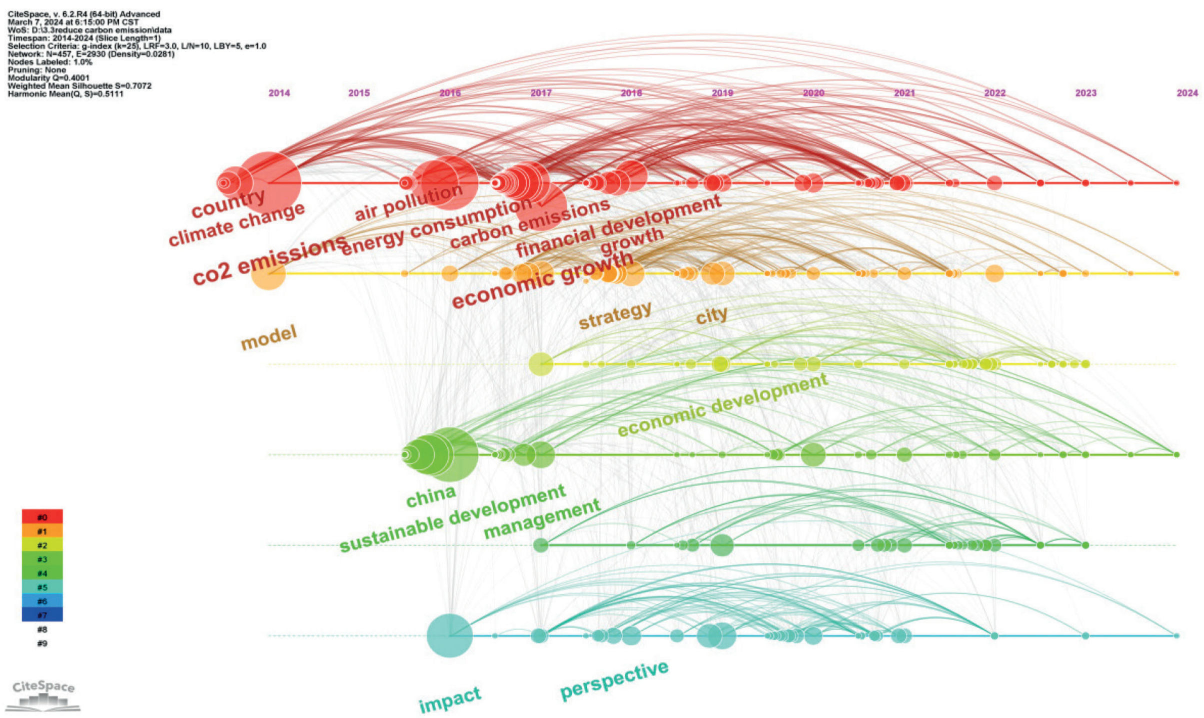

Fig. 6. Keyword timeline chart.

between carbon emission reduction and economic growth [58], and during this period, the focus of research has shifted to the energy transition, i.e., from reliance on fossil fuels to renewable energy sources, and to studying the importance and feasibility of clean energy in achieving the goal of carbon neutrality [59], emphasizing the importance of regulation through environmental policies and the need for new indicators, and emphasizing the regulation and steering of this process through environmental policies [60]. Thirdly, with the intensification of global climate change issues, how to improve energy efficiency has become the concern of most scholars, and the positive impact of technological innovation on carbon emission efficiency [61], the carbon emission trading pilot policy (CETP), etc., can achieve the green and sustainable development of the city by optimizing the industrial structure [62]. From the content of the main concepts in this phase in the time zone map, the meaning and its involved literature found: that the research in this phase further focuses on the practical application and effect of carbon emission reduction and sustainable development, and supports the harmonious development of the environment and the economy from multiple dimensions in a three-dimensional manner.

Logic of the evolution of carbon emission reduction and sustainable development research frontiers: Through the changes in these three stages, it can be observed that the focus of global carbon emission reduction and sustainable development research has shifted from the exploration of basic theories to their application by specific industries, as well as to policy and technology interventions, and then to the integration of carbon emission reduction targets into broader socio-economic development plans, focusing on the realization of a green economy and low-carbon development strategies. This process reflects the tendency of scientific research to shift from basic theory to practical application and the pursuit of broader socio-economic systems change.

Latest Research Frontiers

A keyword timeline is a tool for analyzing and presenting the evolution of a research field over time and can help to understand how the frequency and interrelationships of keywords within a particular topic or field change over time. Research frontiers, which are the most advanced, up-to-date, and promising research topics in a given research field, can be represented by a keyword timeline. As a result, using the keyword co-occurrence function of CiteSpace, the timeline in carbon reduction research was extracted to systematically present the changes in the frontiers of learning environment research. According to Fig. 6, it can be seen that based on the keyword timeline, the keywords can be classified into 6 categories, from top to bottom, renewable energy, carbon emission, spatiotemporal economy, emission reduction, construction, supply chain6 categories. Fig. 6 can be said that they represent the latest research frontiers in the field of global carbon emission reduction research. By categorizing and summarizing them, we can get three frontier themes of this research: carbon emission and sustainable development research, carbon emission reduction, and energy efficiency improvement.

Research on Carbon Emissions and Sustainable Development

The study of carbon emissions and sustainable development is an important research area at the intersection of environmental science and economics [63]. This research area focuses on how to achieve long-term, environmentally friendly economic growth by reducing carbon emissions [64]. The core objective of carbon emissions and sustainable development research is in sustainable development, which involves a deeper understanding of the global carbon cycle, assessing the impacts of human activities on the climate system, and developing and implementing effective climate change mitigation and adaptation strategies. Research can be conducted at multiple scales, including the national, regional, city, and even individual levels. For example, research may focus on the impact of global deforestation on carbon emissions [65], or the transformation of energy production structures within a country [66]. Research at the local and city level might focus on transport systems [67, 68], building energy efficiency [69], and municipal infrastructure improvements.

Carbon Reduction

Carbon emission reduction refers to the reduction of greenhouse gas emissions, such as carbon dioxide, through various means to mitigate the global warming trend [70]. The implementation of carbon reduction strategies involves a wide range of policy, technological, and socio-economic measures aimed at reducing GHG emissions from human activities. The implementation of carbon reduction strategies is a comprehensive task that requires the joint efforts of governments, enterprises, and individuals. At the policy level, governments can take a series of measures, such as implementing a carbon emissions trading system [71], formulating environmental protection laws and regulations, promoting the development and use of clean energy [72], and promoting energy conservation and emission reduction. Meanwhile, technological innovation is also an important means of carbon emission reduction, including the development of energy-efficient production technologies, research and development of carbon capture and storage technologies [73]. In addition, socio-economic measures are also crucial, such as encouraging low-carbon lifestyles, increasing the price of carbon emissions, and advocating the concept of carbon neutrality, to promote active participation in and support for carbon emission reduction in society. In summary, carbon emission reduction is not only a technical challenge but also an important issue for global cooperation, which requires the joint efforts of all parties to achieve the goal of slowing down climate warming and ensuring the sustainable development of the earth's ecological environment.

Improve Energy Efficiency and Reduce Carbon Emissions

Improving energy efficiency and reducing emissions are important tasks for global environmental sustainability. By adopting advanced production technologies and optimizing processes, the energy efficiency of industrial and production processes can be effectively improved, thereby reducing energy consumption and carbon emissions [74]. At the same time, promoting clean energy and encouraging energy-saving practices, such as adopting renewable energy sources, optimizing building design, and promoting electric transport, are also key measures to reduce emissions. These efforts not only reduce the pressure on the Earth's environment, but also help to promote sustainable economic development and realize a green transformation of society.

Conclusions and Outlook of the Study

Reach a Verdict

This study adopts the bibliometric method to track the research dynamics of carbon emission reduction based on the core set of carbon emission reduction papers in the WoS database in the past 10 years, and finds that: (1) Carbon emission reduction research is in the developmental period, forming a core journal with SCI TOTAL ENVIRON, Journal of Cleaner Production, Sustainability, etc.; a core research team with Cai, Bofeng, Shan, Yuli, Dong, Feng, etc.; and a core country with China, the United States, India, etc. as the issuing and research power. Cai, Bofeng, Shan, Yuli, Dong, and Feng as the core research team, and China, the United States, India, and other countries as the core of the publication and research power. (2) Sustainable development, economic growth and consumption, energy efficiency, climate change and drivers, and energy consumption are the five hot topics in the current study of the learning environment. Among them, sustainable development mainly focuses on the in-depth exploration of carbon emission measurement and monitoring, carbon emission reduction technology research, carbon emission reduction policy, and management research; economic growth and consumption mainly focus on clean energy and carbon trading market; energy efficiency research reduces energy demand through energy efficiency research and focuses on reducing energy demand and greenhouse gas emissions through comprehensive energy efficiency strategies; climate change and drivers focuses on analyzing and managing carbon emissions related to climate change; energy consumption mainly focuses on the impact of the new crown epidemic on energy consumption. (3) The process of research evolution has gone through three stages: exploration of basic theories, application in specific industries and policy intervention, and integration of carbon emission reduction targets into socio-economic development plans; research on carbon emissions and sustainable development, carbon emission reduction, and improvement of energy efficiency are the latest frontiers of carbon emission reduction research.

Look Ahead

Looking to the future of carbon emission reduction research, with an eye on global climate change and the goal of sustainable development, future carbon emission reduction research will focus on the development and application of innovative technologies, improving energy efficiency, and promoting the spread of clean energy to achieve more sustainable and environmentally friendly social development. At the same time, in-depth research on the socio-economic impacts of carbon emissions and policy formulation will help to understand the complexity of carbon emission reduction more comprehensively and provide more specific and effective guidance to governments and enterprises. Interdisciplinary cooperation will become an important trend in future research, integrating knowledge from multiple fields, such as engineering, science and technology, and sociology, and jointly exploring more innovative solutions to promote carbon emission reduction research to new heights, and contributing positively to a sustainable future for the earth's environment.

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