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Analyze the Temporal and Spatial Distribution of Carbon Capture in Sustainable Development of Work

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Abstract: This study aims to analyze the temporal and spatial distribution of carbon capture technologies worldwide, examining the economic, social, and political developments reflected in related academic literature. By conducting a comprehensive analysis of over 40,000 related documents from 2004 to June 2024, as well as selecting 108 relevant articles from SSCI and SCI journals, the study explores the development of carbon capture technologies from different perspectives through keyword searches, trend analysis, and relevance ranking. The study finds that, in terms of temporal trends, significant progress has been made in carbon capture technologies since 2009, and their importance has surpassed that of carbon trading, becoming one of the core technologies in addressing climate change. Spatial trend analysis shows that North American and European countries are more inclined to prioritize "carbon capture" technologies, while Asian countries focus more on "carbon trading", reflecting regional differences in economic, policy, and technological development. Although carbon capture technologies hold immense potential for sustainable development, they also face numerous challenges, including balancing technological advancements with economic and policy frameworks. This balance is crucial to ensuring that carbon capture technologies can make a positive contribution to sustainable work, climate action, and environmental sustainability, further transforming the essence of sustainable efforts. To fully realize their benefits, it is essential to recognize and address these challenges.

Keywords: carbon capture; carbon trading; temporal trends; spatial distribution; sustainable development of work

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1. Introduction

Around 1990, the academic community conducted extensive research activities on the impact of fossil fuel emissions on climate change and, as a result, the Clean Air Act Amendments were born, becoming a specific example [1]. The reaction in the American market to this initiative was significant and clear. In an era that highly values environmental issues, carbon capture technology, as a potential solution, is being widely discussed and researched [2]. Carbon capture, commonly referred to as Carbon Capture and Storage (CCS) or Carbon Capture, Utilization, and Storage (CCUS), is a critical technology aimed at reducing industrial and energy-related carbon dioxide (CO_2) emissions to mitigate climate change (Carbon Capture and Storage (CCS) is a key technology for reducing industrial and energy-related sources of carbon dioxide emissions to mitigate climate change. This process involves capturing carbon dioxide at the source, transporting it, and storing it in geological formations or using it in various industrial processes. Carbon Capture, Utilization, and Storage (CCUS) is a key technology that involves capturing carbon dioxide from industrial and energy-related sources, using it for various applications, and storing it safely to prevent its release into the atmosphere. This integrated approach not only includes reducing greenhouse gases but also explores the possibility of using carbon dioxide as a resource. Carbon Capture and Utilization (CCU) technology converts captured carbon dioxide into valuable products such as fuels, chemicals, and building materials, promoting climate action under Sustainable Development Goal (SDG 13).). This process includes capturing CO_2 emissions at the source, transporting them, and storing them in geological formations or using them in various industrial processes [3–5].

Carbon Capture and Utilization (CCU) technology provides an important framework for converting carbon dioxide emissions into valuable products, thereby promoting the Sustainable Development Goal of climate action (SDG 13). However, due to the high energy consumption characteristics of these technologies, their application may shift the burden to other sustainable development goals, such as human health and water scarcity issues. Combining CCU technology with negative carbon energy can mitigate these adverse effects to some extent. This underscores the importance of adopting integrated technology development strategies that align with multiple sustainable development goals [6]. Carbon Capture and Storage (CCS) is considered sustainable, with positive interactions with Sustainable Development Goal 13. However, it requires additional energy, which can have environmental impacts. Despite these challenges, CCS does not hinder the realization of other sustainable development goals, thus becoming a viable option for mitigating climate change [7]. Since around 2009, carbon capture has become an important technological option to help achieve global climate goals. A comprehensive review of relevant data and literature shows that understanding the economic, social, and political developments of carbon capture through carbon trading is crucial. This study, through global trends and spatial distribution approaches, using more than 40,000 literature records from 2004 to June 2024, demonstrates the temporal and spatial trend changes of carbon trading and carbon capture. These trends echo the statistical perspectives of academic research.

2. Materials and Methods

The discussion on carbon capture is multifaceted, focusing on technological advancements, economic feasibility, and policy frameworks. This study is conducted in two phases. First, assess the academic relevance through keywords, then conduct trend analysis based on the long-term characteristics of the carbon capture phenomenon revealed by past datasets in the literature system.

2.1. Keyword Query

Carbon capture, as a technology to reduce greenhouse gas emissions, is widely applied in European and American countries, whereas in Asia, the carbon trading mechanism receives more attention. Carbon trading is a market-based system based on carbon emission allowances, allowing companies to buy and sell carbon emission allowances according to their actual emissions, thereby effectively managing and controlling emissions. This system, by providing economic incentives, encourages companies to adopt carbon capture technologies to reduce emissions, thus achieving greenhouse gas reduction targets. In the carbon trading market, the application of carbon capture technologies helps companies achieve more stringent emission reduction standards and gain a competitive market advantage. Carbon trading also promotes cooperation between companies and drives the realization of global reduction targets. In this study, we conducted keyword searches for "carbon trading" and "carbon capture" using the databases Google Scholar, Web of Science, and Scopus. Through cross-referencing and relevance filtering, a total of 40,600 related documents were found. The documents reflect the extensive academic discussion on the important role of carbon trading and carbon capture technologies in mitigating climate change (see Table 1).

Table 1. A literature review of carbon trading and carbon capture.

Item	**Research Content**
Total Literature	40,600
Search Keywords	Carbon Trading, Carbon Capture
Database	Google Scholar, Web of Science, Scopus
Research Period	Multiple research periods (e.g., 2014–2022, 1992–2021)
Main Research Summary	The important role of carbon trading and carbon capture technologies in mitigating climate change
Mashari et al. [8]	Analyzed 506 articles on sustainable finance and carbon trading from 2014–2022, highlighting the need for further research connecting these two fields effectively.
Su and Yu [9]	Analyzed 4408 scholarly articles on carbon finance from 1992–2021, noting rapid publication growth and interest in carbon capture, economic growth, and carbon price forecasting.
Podder et al. [10]	Provided a comprehensive overview of carbon emissions from fossil fuel consumption and the importance of Carbon Capture and Storage (CCS), detailing mechanisms such as pre-combustion, post-combustion, and direct air capture.
Fujita [11]	Reviewed 626 articles on embodied carbon emissions and international pollution identification methods from 1994–2023, discussing the role of carbon trading in controlling emissions.
Kim [12]	Discussed accounting methods for early carbon sequestration investments and trades, emphasizing the need for standardized credit rating to ensure the integrity of carbon sequestration credit trading.
Otto and Gross [13]	Systematically reviewed 115 articles on communication practices regarding Carbon Capture and Storage (CCS), underlining the importance of effective stakeholder engagement.
Altman [3]	Discussed the extensive debate and research on incorporating carbon capture and storage technologies under the Clean Development Mechanism (CDM) of the Kyoto Protocol. (The Clean Development Mechanism (CDM) is an important component of the Kyoto Protocol aimed at promoting emission reductions while encouraging sustainable development in developing countries. It allows developed countries (Annex I countries) to fund projects in developing countries (non-Annex I countries) and receive Certified Emission Reductions (CERs) to meet their emission reduction commitments.)
Malan and Malan [14]	Analyzed challenges in comparing emission reductions and carbon sequestration, particularly issues related to the duration of storage for captured carbon dioxide.
Maitland [15]	Discussed carbon capture and storage technologies, emphasizing the need for tighter integration of materials and process design to optimize carbon dioxide capture and utilization processes.
Yu and Xu [16]	Scientometric analysis of Carbon Emission Trading (CET), highlighting the growth in publication numbers in the field and its major research areas, providing a clear picture of the current state and future trends. (Carbon Emission Trading (CET) is a market-oriented approach to reducing emissions by setting an emission cap and allowing entities to buy and sell allowances to reduce greenhouse gas emissions. This system is designed to incentivize businesses to reduce emissions cost-effectively while promoting sustainable development.)

In summary, these studies indicate that the body of literature on carbon trading and carbon capture is growing, reflecting their critical role in global climate change mitigation efforts. By analyzing trends in carbon capture and carbon trading from 2004 to 2024, this study conducted comprehensive statistical and spatial analysis of over 40,600 documents from January 2004 to June 2024 and selected 108 relevant SSCI and SCI papers to explore the development of carbon trading and carbon capture from different perspectives (as shown in Figure 1).

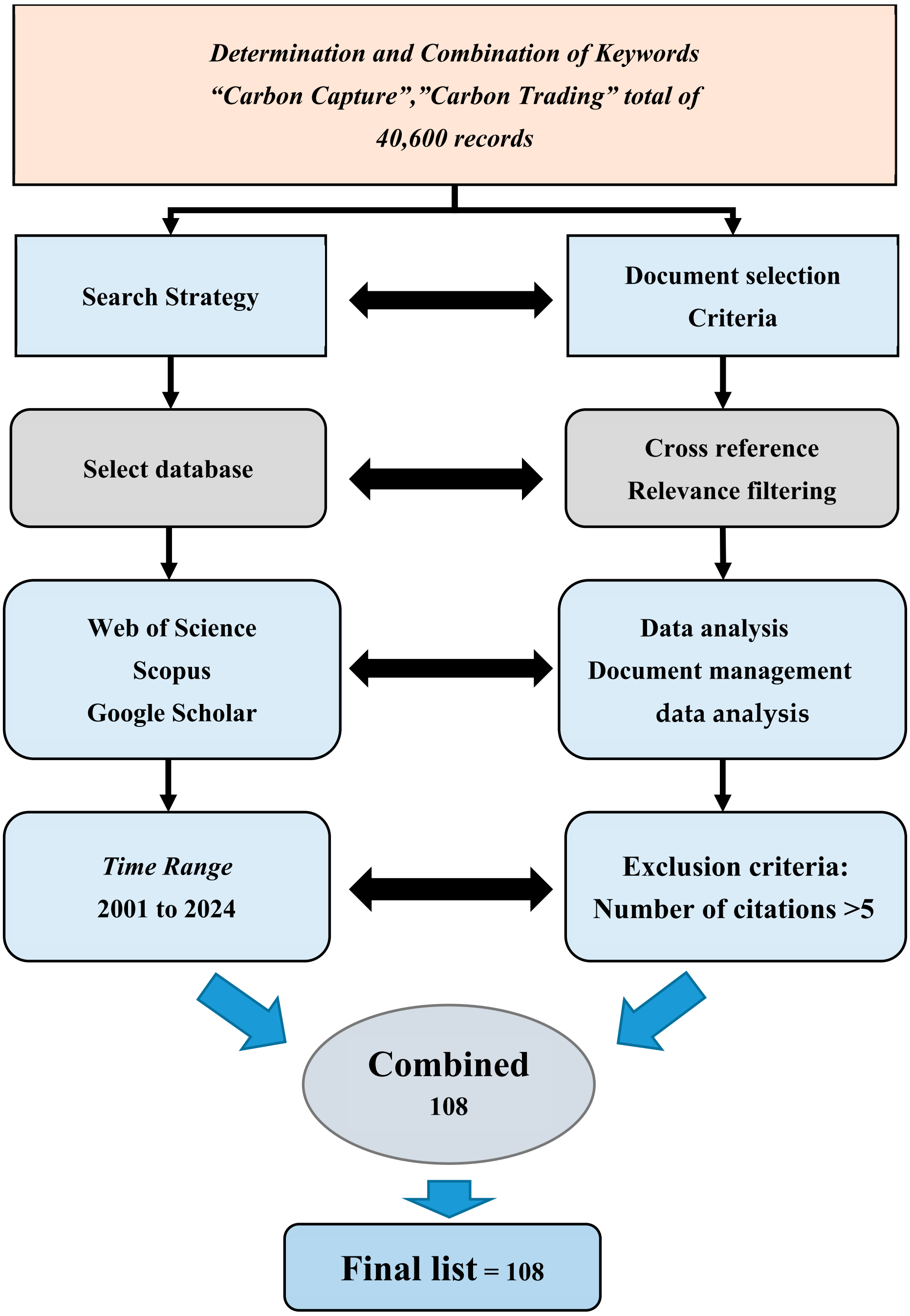

Figure 1. Flowchart of the literature selection procedure for carbon capture and carbon trading research.

2.2. Literature Screening and Analysis Steps

In the methodology section, our literature screening and analysis steps are as follows:

(1) Database Search:
- Using three major academic databases, Google Scholar, Web of Science, and Scopus, we conducted a comprehensive search with the keywords "carbon trading" and "carbon capture", initially obtaining 40,600 related documents.

(2) Screening Process
- Time frame: Limited to documents published from January 2004 to June 2024.
- Preliminary screening: Conducted based on titles, abstracts, and keywords to narrow down to approximately 40,000 documents to ensure the efficiency of the screening process.

(3) Cross-referencing and Relevance Filtering
- Utilized the cross-referencing features within the databases for mutual referencing and relevance filtering of the documents.

(4) Keyword Search
- For the preliminarily screened documents, performed more specific keyword searches, expanding the keyword range to CCS, CCU, "carbon trading market", and other related fields to enhance screening precision.

(5) Trend Analysis
- Used trend analysis tools to analyze the selected documents to determine research trends and development status of carbon capture and carbon trading.
- In the field of carbon capture technology research, the selection of appropriate keywords is paramount for capturing emerging trends and ensuring comprehensive coverage. For instance, in the realm of technological innovation, keywords such as "direct air capture", "metal-organic frameworks (MOFs)", "superbase-derived ionic liquids (SILs)", and "mixed matrix membranes" are instrumental in identifying the latest advancements. In terms of economic and policy aspects, exploring keywords like "economic feasibility", "policy framework", "carbon trading", and "quota allocation" aids in analyzing the economic and policy impacts. Regarding sustainability and environmental impact, terms like "sustainable solvents", "phase-change absorbents", and "nanoparticle-enhanced solvents" help locate relevant research projects. Additionally, regional and spatial distribution keywords such as "spatial distribution", "regional climate adaptability", and "site selection" should be used. For research on integrating carbon capture technology with renewable energy, terms like "renewable energy DAC", "wind power", and "U.S. 45Q tax credit" are essential. Through these strategies, researchers can effectively capture the latest trends in carbon capture technology, ensuring a comprehensive understanding of the field.

(6) Secondary Screening
- Peer-reviewed:
  Only peer-reviewed academic articles are selected, excluding any non-peer-reviewed documents such as conference abstracts, news reports, technical reports, and white papers.
- Publication source:
  Only articles published in journals indexed by SSCI, SCI and ESCI are considered. These journals possess high influence and reputation in their respective fields and can provide reliable research results.
- Relevance to the topic:
  Literature must directly relate to carbon capture technology. This includes, but is not limited to, the principles, methods, technological improvements, application cases, economic assessments, and environmental impact evaluations of carbon capture.
- Language:
  Only articles published in English-language journals are selected to ensure that researchers can fully comprehend and interpret the content.
- Rigorous research methods:
  Preference is given to articles employing strict and transparent research methods, such as those with clear experimental design, data analysis, and result interpretation.
- Citation frequency:
  The citation count of the literature is considered, with preference given to articles with high academic impact and citation rates. The minimum citation count is five.
  A secondary screening was conducted, focusing on documents with significant academic impact, high citation rates, and high journal impact factors, ultimately selecting 108 relevant SSCI, SCI and ESCI documents.

(7) Software Tools Utilization

- Literature management: Managed and organized literature using EndNote and Zotero.
- Data analysis: Performed statistical analysis, including trend analysis and spatial analysis, using Microsoft Excel and R.
- Data visualization: Generated charts and graphs using Tableau for a more intuitive presentation of the analysis results.

This systematic approach ensures the accuracy of literature screening and comprehensiveness of analysis, enabling us to comprehensively understand the research trends and development dynamics of carbon capture and carbon trading from 2004 to 2024.

3. Research Results: Temporal Trends

3.1. The Impact of Technology on Sustainable Development

For many years, due to the urgent need to reduce the adverse effects of carbon dioxide emissions on global climate, CCS has made significant progress. The Kyoto Protocol, signed in 1997 and effective in 2005, greatly increased interest in CCS technology and integrated it into the CDM to achieve carbon dioxide reduction targets [3]. The Kyoto Protocol has further highlighted the importance of CCS in global emission reductions since it came into effect in 2005 [3]. CCS has consistently been regarded as a potential yet underutilized solution that may play a crucial role in reducing the costs of achieving climate stability [17] and enhancing the flexibility of emission reduction strategies [4]. However, the widespread deployment of CCS still faces multiple challenges, including high capital costs, low capture efficiency, and the need for policy support and international cooperation [18,19].

As a supplementary method, CCU is gradually emerging, aiming to convert captured carbon dioxide into valuable products such as fuels, chemicals, and building materials, thus providing economic incentives to reduce carbon dioxide emissions [20,21]. Despite the fact that some CCS and CCU technologies have matured technically, their large-scale application is still constrained by economic, technical, and political barriers [18]. Scientific research has been continuously exploring innovative materials and methods, such as ionic liquids and advanced adsorbents, to enhance the efficiency and cost-effectiveness of carbon dioxide capture [19,22]. Therefore, controlling methane emissions can effectively reduce tropospheric ozone and radiative forcing, further supporting integrated reduction approaches [23]. In order to reduce pollutants and carbon dioxide emissions, advanced combustion technologies including gasoline compression ignition have been developed [24], although these technologies still face challenges [23]. Besides the challenge, the simultaneous presence of water and carbon dioxide also brings challenges, but the use of molecular sieves to capture hydrocarbons still shows potential in reducing industrial emissions [25]. CCU in recent years has made significant progress, introducing new materials and methods such as porous silica-based materials, ionic liquids, and membrane technology. These innovations have improved capture efficiency and reduced costs [26–28]. Research and development of new low-cost carbon capture technology, utilizing cold nitrogen refrigerants to minimize energy consumption and water resources usage, have also achieved breakthroughs [29]. Direct Air Capture (DAC) technology, such as the use of short-chain tetra (n-alkyl) ammonium hydroxide, has also become a potential method for capturing carbon dioxide directly from the atmosphere [30] (Direct Air Capture (DAC) is a cutting-edge technology aimed at mitigating climate change by removing carbon dioxide directly from the atmosphere. This method is gaining attention for its significant potential to address traditional carbon dioxide emission challenges and help achieve net zero emissions. Emission Trading Systems (ETS) are market-based mechanisms for reducing emissions by setting an emission cap and allowing the trading of emission allowances. These systems have been implemented globally with varying designs and impacts, aiming to encourage emission reductions and promote green technologies.). These technological developments are of great significance for transitioning to new sustainable energy sources while reducing greenhouse gas emissions [22,31].

3.2. Economic and Policy Considerations

This section primarily examines the temporal trends in carbon capture and carbon trading, alongside the significance of these technologies in global carbon reduction efforts. The interaction between carbon trading and carbon capture technologies is highly intricate, involving various domains such as economics, regulation, and technology. Mechanisms like Emission Trading Systems (ETS) offer a market-based approach to curbing greenhouse gas emissions by allowing for the trade of emission permits or credits. The formulation and execution of carbon trading mechanisms crucially influence the advancement and efficacy of Carbon Capture and Storage (CCS) technologies. These mechanisms set the marginal cost of carbon emissions, which is affected by the stringency of emission caps and the timing of their implementation. Consequently, fluctuations in carbon prices significantly impact the deployment and investment in CCS technologies. The marginal cost associated with carbon emissions is contingent on the rigidity of emission limits and the schedule of their establishment, which in turn directly influences the variability of carbon prices. This fluctuation has significant implications for the deployment and financial commitment towards CCS technology [32]. By linking different ETS systems, allowing emission permits from one system to be traded in another, overall compliance costs can be reduced, market liquidity enhanced, and spillover effects of emissions minimized, thereby promoting the expansion of CCS technology. However, the success of such linkages depends on the design of the ETS, political intentions, and existing economic and political relationships [33]. The Paris Agreement encourages countries to regularly review their climate policies and compliance progress, thereby promoting the development of carbon markets and indirectly supporting CCS technology [33]. Although such connections bring multiple benefits, the linkages between different ETS also introduce new challenges and uncertainties, such as price fluctuations, the need for transparent subsidy and cap-setting rules, which are crucial for maintaining market stability and promoting investment in CCS technology [34,35]. Additionally, for large-scale point source capture of carbon dioxide and its storage in geological formations, CCS technology is extremely costly, usually requiring national support or public–private partnerships to achieve [3]. This integration demonstrates the potential of CCS technology as part of a broader carbon trading scheme, thereby enhancing its economic viability. Moreover, innovative carbon trading schemes such as double carbon trading further balance emission reduction targets with social welfare, promote low carbon energy consumption, and support CCU [36]. The international CCS projects, which involve capturing carbon dioxide in one country and transporting it to another country for storage, also bring regulatory and liability challenges that must be addressed to promote global deployment [37]. To sum up, the interaction between carbon trading and CCS is extremely complex, which is crucial for achieving deep emission reductions and global emission targets. Through carefully designed and linked carbon markets, the necessary economic incentives and regulatory frameworks can be provided to support the comprehensive application of CCS technology, contributing to global climate change mitigation.

3.3. Trends in Carbon Trading and Carbon Capture

According to Figure 2, since 2004, carbon trading has received widespread attention, reaching its peak around 2008. However, its popularity has significantly declined thereafter. Conversely, carbon capture technology has seen significant growth since 2011, peaking in 2021, and continues to attract attention. Early carbon capture technology mainly relied on post-combustion capture using aqueous amine scrubbing, facing challenges of high regeneration energy and solvent degradation [28]. After 2011, innovation expanded to include pre-combustion and oxy-fuel combustion technologies, the latter utilizing pure oxygen to produce flue gases rich in carbon dioxide, thereby simplifying the carbon dioxide separation process [27].

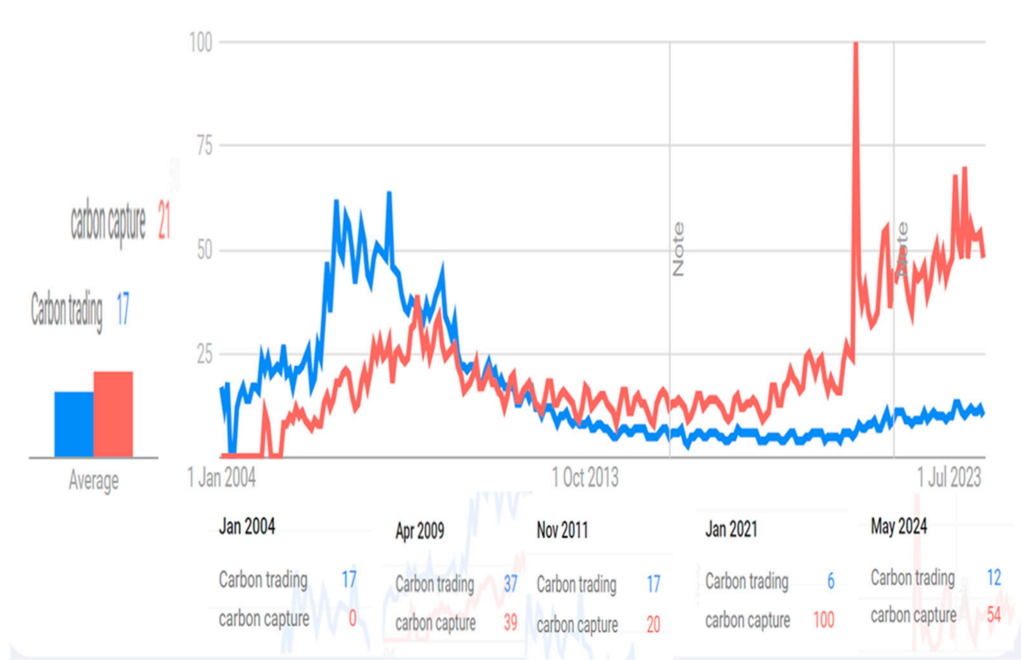

Figure 2. Trends in literature on carbon trading and capture (2004–June 2024).

In 2021, CCS made significant breakthroughs, addressing various challenges related to efficiency, cost, and scalability. One notable advancement was the development of mixed matrix membranes, greatly enhancing carbon dioxide permeability [38]. Direct air capture technology has also made progress in areas such as Metal–Organic Frameworks (MOFs) and superbasic-derived ionic liquids (SILs), demonstrating efficient carbon dioxide absorption performance and excellent cyclic stability [39] (Metal–Organic Frameworks (MOFs) are a class of crystalline materials with a porous structure formed by connecting metal ions or clusters with organic ligands. These materials are noted for their unique properties and wide range of applications. MOFs are known for their high surface area, tunable pore size, and multifunctionality, suitable for various industrial and scientific applications. Superalkaline Ionic Liquids (SILs) are ionic liquids that have received significant attention for their unique properties and diverse applications. These ionic liquids contain superalkaline cations, giving them high alkalinity and the ability to dissolve cellulose and other difficult-to-dissolve substances.). In addition, research focuses on more economical and sustainable solvents, such as phase-change absorbents and nanoparticle-enhanced solvents, to improve carbon dioxide absorption performance and reduce energy demand [22]. New developments also include a system called "reverse" SILP, which has improved carbon dioxide/N2 separation performance and carbon dioxide absorption capacity, overcoming the limitations of traditional SILP [40] (Supported Ionic Liquid Phase (SILP) materials represent a versatile and innovative approach in various fields such as catalysis, composites, and biocatalysis. These materials combine the unique properties of ionic liquids with the structural advantages of solid supports, enhancing stability, reusability, and efficiency.). Polymer Continuous Assembly (CAP) technology can produce ultra-thin membranes with high carbon dioxide permeability and excellent gas separation selectivity, further advancing membrane-based carbon dioxide capture methods [41]. Finally, the techno-economic evaluation of combining DAC with renewable energies such as wind power shows the potential to reduce costs and improve economic feasibility, especially with the support of the US 45Q tax credit incentive policies [42].

Overall, the average global search interest in "carbon trading" has fallen below "carbon capture". Carbon capture technology is gradually becoming one of the core strategies worldwide to address climate change. Various carbon reduction methods are being widely explored, particularly improvements in energy use technology and efficiency. For example, electrochemical, photochemical, and photo electrochemical processes can convert carbon dioxide into useful hydrocarbons [43,44]. Energy efficiency measures such as building lighting and power decarbonization are regarded as efficient emission reduction pathways [45]. The American industrial sector achieves targeted decarbonization through measures such as strategic energy management and smart manufacturing, which are crucial for achieving sustainable development [46]. Furthermore, combining renewable energy with storage technology provides a scalable energy solution while controlling atmospheric carbon dioxide levels [47]. According to the trend changes shown in Figure 2, we can observe that the research interest in "carbon trading" increased significantly from 2004 to 2011, peaking in 2008. This period of peak interest can be traced back to the formal implementation of the Kyoto Protocol in 2005, which prompted global attention to the carbon trading mechanism as an important market-based tool for achieving emission reduction targets. Many countries and companies began to explore and implement ETS, leading to a sharp increase in research interest. However, after 2011, the research enthusiasm for carbon trading dropped significantly, which may be related to the 2008 global economic crisis and the subsequent economic downturn. During economically difficult times, investment in and attention to environmental measures often decrease. Additionally, some carbon trading markets, such as the EU ETS, faced issues of excess allowances and plummeting carbon prices in their initial stages, further weakening market confidence and leading to a decline in research interest. At the same time, from 2011 onwards, research interest in CCS technology increased significantly. This shift in trend partly stems from the challenges and limitations faced by the carbon trading market, prompting a focus on alternative emission reduction technologies. Moreover, technological breakthroughs and cost reductions around 2011, such as the development of pre-combustion and oxy-fuel combustion technologies, greatly improved the efficiency and economics of the technology, further driving the rise of CCS research. In 2015, the signing of the Paris Agreement further reinforced the focus on CCS technology. The agreement called for strong measures by countries to achieve emission reduction targets, promoting CCS as a key technology for reaching these goals. Since then, research interest in CCS has continued to grow, reaching a new peak in 2021. This phenomenon can be attributed to several factors:

- Technological advancements: Innovative technologies such as hybrid matrix membranes, MOFs, and SILs have improved the efficiency, cost-effectiveness, and operability of CCS.
- Policy support: Policies like the US 45Q tax credit policy have provided economic incentives for CCS projects, boosting investor confidence.
- Strengthening of global climate policies: Under the framework of the Paris Agreement, countries have enhanced their climate targets, increasing the focus on CCS.

4. Research Results: Spatial Distribution

According to the trend index from 2004 to 2023, spatial distribution revealed regional preference differences in various climate-related themes. North American and European countries lean more towards "carbon capture and storage", while Asian countries show greater interest in "carbon trading" (see Figure 3). Figure 3 is a color-coded world map showing the distribution of global carbon capture and carbon trading activities from 2004 to June 2024. The intensity of the red shading indicates the level of carbon capture efforts in different regions: North America, Europe, and East Asia are shaded more deeply in red, indicating higher activity levels, while areas such as Africa, Central Asia, and parts of South America are shaded more lightly, indicating lower activity levels. The blue shading indicates the attention to carbon trading in different regions, with deeper blue shading in Asian regions, particularly in countries like China and India, indicating a higher interest in carbon trading activities. Regions like Greenland and central Sahara are colorless, indicating a lack of carbon capture or carbon trading activities. This map reveals that industrialized regions are more actively implementing carbon capture technologies, demonstrating their technological and economic capabilities; meanwhile, some Asian countries show significant activity in carbon trading. The significant disparities between developed and developing regions reflect the unequal response to climate change globally, underscoring the importance of promoting global collaboration and technology transfer.

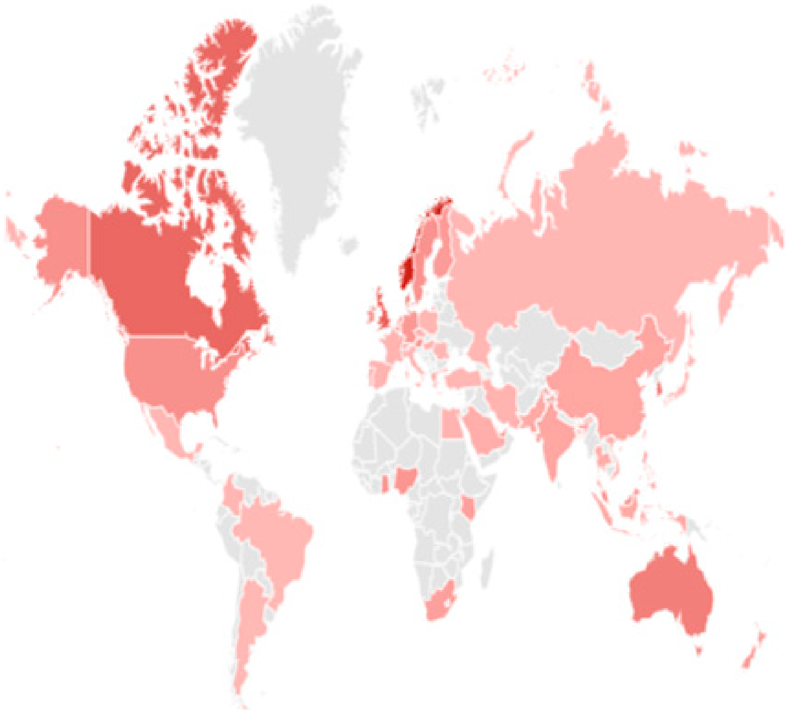

Figure 3. Global carbon capture spatial distribution from 2004 to June 2024.

The different economic, policy, and social driving factors are the main reasons for the regional priority differences. In North America and Europe, CCS technology is seen as a key means to significantly reduce greenhouse gas emissions while still using fossil fuels. In the US, particularly in areas where coal is widely used, it is in a favorable position to apply DAC technology due to the mature policy environment, abundant funding opportunities, and low-carbon energy supply. However, even with a supportive regulatory environment, advancing CCS projects in the US still faces challenges related to underground resource ownership and state-level jurisdiction, which must be properly addressed to proceed smoothly [48].

In the European Union, established climate policies and a supportive political environment favor the deployment of CCS technology [48]. European countries are working to integrate CCS into a broader climate policy framework that includes not only the expansion of renewable energy but also cogeneration programs. In Germany, for example, the competition between CCS technology and renewable energy technology is a key consideration, while public opposition to carbon dioxide storage projects poses a significant obstacle [49]. The EU is particularly active in promoting maritime projects and is committed to clarifying the classification of carbon dioxide in international regulations [48]. At the same time, build a cost-effective global CCUS framework aimed at matching carbon sources with carbon sinks to achieve significant reductions in carbon dioxide emissions [50]. In addition, the EU focuses on subsidizing upstream segments in CCS technology innovation, benefiting suppliers and enhancing economic efficiency [51]. However, because the EU faces challenges in public planning and regulation, especially in the spatial reorganization of power generation and transmission systems, efficient installation of CCS-related infrastructure is necessary [52]. Some European countries, such as the Netherlands and the United Kingdom, have public attitudes towards industrial carbon capture and storage projects that are neutral to slightly positive, influenced by climate change, safety, and employment expectations [53]. The EU is also addressing regulatory and legal challenges supporting the development of the CCUS supply chain, ensuring its consistency with international law and creating a favorable environment for financial viability [54]. The results of the life cycle assessment of the potential benefits of integrating CCUS technology into the energy supply sector show a significant reduction in the global warming potential in countries such as Italy and Poland [55].

Asian countries such as China, Japan, and South Korea are actively promoting the development of carbon trading systems, which are seen as a market-oriented emission reduction strategy (see Figure 4). These countries have explored the potential of linking carbon emission trading systems with each other, demonstrating that a unified market can significantly enhance cost efficiency, promote economic benefits, and improve market liquidity and trading scale [56]. Asian emerging economies like China are developing carbon market mechanisms, creating domestic carbon credit demand and connecting with regional and global carbon markets [57]. Asian emerging economies such as China are developing carbon market mechanisms, creating domestic carbon credit demand and connecting with regional and global carbon markets [58]. However, developing countries in Asia still face challenges in public acceptance and stakeholder management in the deployment of CCS technology, which need to be strategically addressed to promote the adoption of CCS [59]. Despite facing challenges, China still possesses the potential to deploy DAC technology, thanks to its well-established policy and funding environment [60].

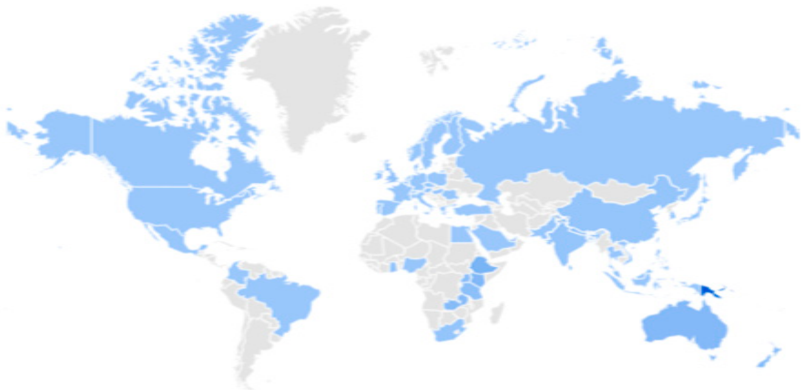

Figure 4. Global spatial distribution of carbon trading from 2004 to June 2024.

Figure 4 is a world map showing the trends in carbon trading distribution from 2004 to June 2024. The varying shades of blue represent the levels of carbon trading activities across different countries, with darker areas indicating more active carbon trading, such as in Europe and North America, while lighter or colorless areas such as most parts of Africa and some regions in Asia show fewer or non-existent carbon trading activities. The map reveals a slight increase in carbon trading activities among some emerging economies in Asia, indicating a growing participation in the carbon market in these regions. This distribution helps in understanding the global participation in the carbon market and identifying areas that may require policy intervention or support to enhance participation in carbon trading programs. As of 2011, many European, North American, and some Asian countries began to shift their focus to CCS, with a significant increase in attention towards achieving net-zero emissions targets. By 2022, this scope of attention had expanded to 55 countries, with Norway, Singapore, Denmark, Canada, and the UK being particularly prominent. Trend data indicate that the application of carbon capture technology has extended widely over time and space, with its influence gradually spreading from Europe and the Americas to Asia and Africa (see Figure 5). The United States has played a key role in the development and innovation of CCS technology, but it is not the only leader in this field. The United States has established a mature carbon dioxide injection policy framework, mainly applied to enhance oil recovery, and has made significant progress in CCS research [61,62]. However, the development of carbon dioxide capture and storage technology relies on global cooperation. As the largest greenhouse gas emitters, the

United States and China are collaborating in the field of CCS through initiatives such as the Clean Energy Research Center, leveraging the complementary strengths of both countries to accelerate the global deployment of CCS [63]. Norway and other countries have also participated in several important CCS projects, although some projects are facing cancellation or delays [64]. The European Union, Australia, and Canada are also actively contributing to the regulation and promotion of CCS, emphasizing the importance of international cooperation and a unified regulatory framework [65].

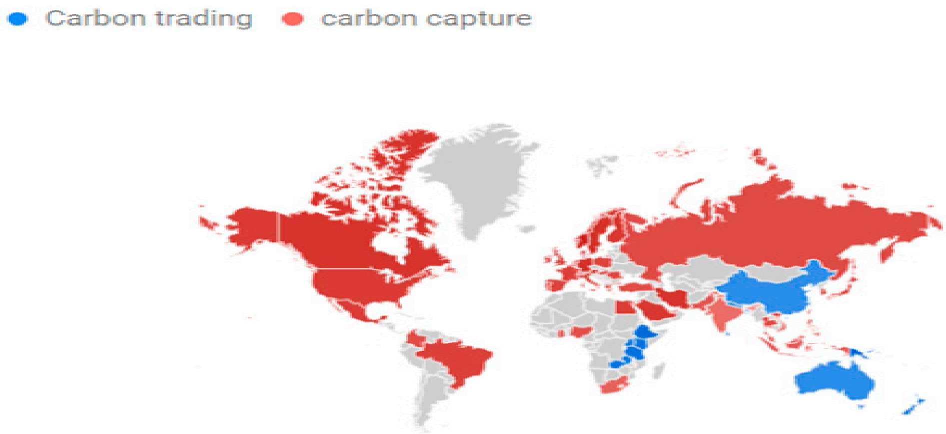

Figure 5. Global carbon trading and carbon capture spatial distribution 2004 to June 2024.

Effective CCS regional cooperation can be achieved through multi-party research integration and addressing various challenges. The integration of regional carbon markets into a unified national market helps strengthen resource integration and regulation. For example, China is committed to connecting its pilot regional markets to the national carbon market to establish a comprehensive spillover network, promoting information transfer and risk management [66]. A fair and efficient quota allocation plan can reduce economic costs and ensure the equitable distribution of emission reduction tasks, as demonstrated by China's multi-standard quota allocation plan [67]. In addition, regional climate adaptability is particularly important in the deployment of DAC technology, and site selection must be carefully made based on regional climate conditions to optimize performance and reduce costs [68]. The cooperation between major greenhouse gas emitters such as the United States and China on CCS projects fully demonstrates that through collaborative efforts, leveraging their respective comparative advantages, and ensuring mutual benefit, significant global impacts can be achieved [63]. Further, technological innovations, such as the application of imidazolium-based ionic liquids and bicarbonate mechanisms, can significantly enhance CO_2 capture efficiency [69,70]. The transition to a low-carbon economy also requires a skilled workforce capable of implementing and managing carbon capture technologies. The U.S. Department of Energy's Carbon Sequestration Research experience program demonstrates efforts to build a talent pipeline in CCUS, emphasizing sustainable development education that is diverse and inclusive. This program aims to prepare young leaders for the clean energy transition, highlighting the importance of workforce development in achieving sustainable work outcomes [71]. Figure 5 illustrates the geographical distribution of global carbon trading and carbon capture activities from 2004 to June 2024, with color coding to differentiate the level of participation by region. In the map, red areas indicate countries implementing carbon capture technologies, while blue areas show countries with established carbon trading systems. The main findings reveal that North America, Europe, and parts of Asia are predominantly marked in red, indicating a high level of participation in carbon capture activities in these regions. Meanwhile, countries marked in blue are relatively fewer and are concentrated mainly in Europe and North America, suggesting that carbon trading activities are somewhat limited but strategically significant in these areas. Overall, the adoption of carbon capture technologies is more widespread globally. This trend emphasizes the global focus on technological sequestration methods and the demand for related sustainable job roles, highlighting the importance of enhancing occupational safety training in carbon capture fields.

5. Conclusions

The aim of this research is to analyze the temporal and spatial distribution of global carbon capture and carbon trading technology, exploring the economic, social, and policy challenges in their development and implementation. The results indicate significant differences in the priorities of carbon capture and carbon trading across various regions, with differing temporal trends as well. Firstly, carbon trading research peaked in 2008 due to the Kyoto Protocol but declined after 2011 due to economic challenges and market limitations. This indicates that early policy promotion and market boom were followed by economic recession and market integration, affecting its prominence. Secondly, interest in carbon capture research has steadily increased since 2011, driven mainly by technological advances, policy support, and growing global attention to climate change. The establishment of technological innovations and policy frameworks has made carbon capture an important means of mitigating climate change. Spatially, North America and Europe have placed more emphasis on carbon capture technology, whereas Asia has focused on carbon trading. This phenomenon can be attributed to widespread coal use in North America and Europe, mature policy frameworks, and ample financial resources. In Asia, the emphasis on carbon trading is due to the need to coordinate emission reduction strategies and achieve carbon removal through technologies such as enhanced weathering and reforestation. A third research outcome shows the global carbon trading trend from 2004 to 2024 (Figures 4 and 5), further supporting the aforementioned spatial and temporal trends, particularly with the significant fluctuations brought about by changes in policy and market environments. However, differences between regions and uneven technological maturity have limited the promotion of carbon capture technology. Specifically, developed countries, because of their financial and technological strength, have made initial progress in carbon capture technology, gradually forming a substantial industry chain, whereas developing countries, due to lack of resources and technology, rely on international cooperation and assistance to promote related technology applications. Additionally, the operation of carbon trading markets reflects the role of policy support and market mechanisms, with regional market maturity having a positive impact on the promotion of carbon capture technology.

Therefore, this research reveals that integrating CCS technology with sustainable work practices involves multiple challenges in the economic, social, and policy dimensions. The economic challenges of CCS technology mainly stem from its high costs, encompassing phases such as CO_2 capture, separation, purification, and transportation. Without policy support and incentive measures, these costs are economically challenging to accept. Moreover, industries implementing CCS technology will face increased operating costs, potentially leading to a decline in their international competitiveness, especially when competitors do not bear similar costs. This scenario could shift employment and economic activities to regions with less stringent carbon policies. The absence of market mechanisms that penalize CO_2 emitters and incentivize the use of captured CO_2 products further complicates the economic feasibility of CCS technology. From a social perspective, the transition to CCS technology might lead to job losses in traditional industries. However, it also creates new job opportunities in emerging green sectors. Therefore, ensuring a just transition requires appropriate policy support to facilitate retraining and reemployment of workers. Additionally, transitioning to sustainable work modes (such as hybrid work models) must consider geographic inequalities and ensure that different regions and socioeconomic groups have equitable access to opportunities.

In conclusion, despite the comprehensive analysis of carbon capture and carbon trading trends presented in this research, there are limitations regarding data sources, regional complexity, and the time scope. Based on the findings and limitations of the research, for a deeper understanding of the differences in policy effectiveness across regions, future studies should conduct detailed regional analyses. Additionally, exploring the long-term impacts of policy changes on the adoption of CCS and carbon trading technologies has become an urgent need. Identifying methods to overcome barriers in CCS technology adoption, such as financing, technology, and market mechanisms, is crucial. Lastly, analyzing the impact of global economic trends on global carbon markets and carbon trading mechanisms will help formulate more comprehensive and effective strategies to promote the development and application of carbon reduction technologies.

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