Erzincan Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
2024, ÖZEL SAYI, 143-159
ISSN: 1307-9085, e-ISSN: 2149-4584
Araştırma Makalesi

Erzincan University
Journal of Science and Technology
2024, SPECIAL ISSUE, 143-159
DOI: 10.18185/erzifbed.1525074
Research Article

# Biomass-Derived Adsorbents for $CO_2$ Capture: Trends and Bibliometric Insights

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**Received:** 30/07/2024, **Accepted:** 29/12/2024, **Published:** 31/12/2024

**Abstract**

Increased fossil fuel usage and deforestation disrupt CO2 balance, exacerbating climate change. A multifaceted approach should be implemented to mitigate the effects of climate change, including sustainable resource management and increased utilization of alternative energy sources. In this process, CO2 capture has emerged as a promising method, with adsorbents playing a critical role. Currently, biomass-based adsorbents, especially those derived from organic bio-waste, are materials of significant interest in the field of CO2 capture due to their unique properties and environmental advantages. This study presents a comprehensive bibliometric analysis of research conducted on adsorbents with high CO2 capture capacities derived from biomass or organic waste sources, aiming to identify trends in this field and evaluate methodologies. Since 1995, over 1500 scientific publications were collected based on selected keywords and manually screened for relevance. In the bibliometric analysis, key data such as authors, affiliated institutions, countries, and research areas were presented, and datasets were compiled for performance analysis and scientific mapping. Web of Science (WoS), one of the most commonly used multidisciplinary databases today, was utilized for data collection and analysis, and VOSviewer software was employed for mapping. In conclusion, this study maps the landscape of the relevant field by identifying significant contributors, relevant keywords, field categories, and research approaches, serving as a strategic tool for researchers to recognize progress, trends, and gaps to guide future studies.

**Keywords:** $CO_2$ Capture, bio-adsorbent, biochar, bibliometric analysis

**Biyokütle Türevi Adsorbanlarla $CO_2$ Yakalama: Eğilimler, Teknolojiler ve Bibliyometrik İçgörüler**

**Özet**

Fosil yakıt kullanımının artması ve ormansızlaşma, CO2 dengesini bozarak iklim değişikliğini şiddetlendirir. İklim değişikliğinin etkilerini hafifletmek için sürdürülebilir kaynak yönetimi ve alternatif enerji kaynaklarının artırılmış kullanımı gibi çok yönlü bir yaklaşım uygulanmalıdır. Bu süreçte, adsorbanların önemli bir rol oynadığı CO2 yakalama, umut verici bir yöntem olarak ortaya çıkmıştır. Şu anda, organik biyo-atıklardan elde edilenler başta olmak üzere, biyokütle bazlı adsorbanlar, benzersiz özellikleri ve çevresel avantajları nedeniyle CO2 yakalama alanında büyük ilgi görmektedir. Bu çalışma, biyokütle veya organik atık kaynaklarından elde edilen yüksek CO2 yakalama kapasiteli adsorbanlar üzerine yapılan araştırmaların kapsamlı bir bibliyometrik analizini sunarak bu alandaki eğilimleri belirlemeyi ve metodolojileri değerlendirmeyi amaçlamaktadır. 1995'ten bu yana, seçilen anahtar kelimelere dayalı olarak 1500'ün üzerinde bilimsel yayın toplandı ve uygunluk açısından manuel olarak tarandı. Bibliyometrik analizde, yazarlar, bağlı kurumlar, ülkeler ve araştırma alanları gibi anahtar veriler sunulmuş ve performans analizi ile bilimsel haritalama için veri setleri derlenmiştir. Veri toplama ve analiz için günümüzde en yaygın kullanılan multidisipliner veri tabanlarından biri olan Web of Science (WoS) kullanılmış ve haritalama için VOSviewer yazılımı kullanılmıştır. Sonuç olarak, bu çalışma, önemli katkıda bulunanları, ilgili anahtar kelimeleri, alan kategorilerini ve araştırma yaklaşımlarını belirleyerek ilgili alanın genel bir haritasını çıkarır ve araştırmacıların ilerlemeyi, trendleri ve boşlukları tanımasına yardımcı olan stratejik bir araç olarak hizmet eder, böylece gelecekteki çalışmalara rehberlik eder.

**Anahtar Kelimeler:** $CO_2$ yakalama, biyo-adsorban, biyoçar, bibliyometrik analiz



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## 1. Introduction

The increase in human population has led to excessive consumption, paving the way for industrialization. Within this progress, the global average concentration of $CO_2$ has also significantly increased at an annual rate of 0.5% since 1959, reaching 419 ppm in 2022 [1]. The increase in fossil fuel usage and deforestation contributes to the disruption of the $CO_2$ balance in the atmosphere, the rise in $CO_2$ levels, and consequently, to climate change. Nowadays, effects of climate change can be summarized as follows: heavy droughts, alterations in rainfall patterns, extreme heatwaves, melting of glaciers, and rising sea levels, impacting terrestrial environments [2]. Developing sustainable approaches to reduce $CO_2$ emissions is crucial for mitigating these impacts of climate change. Among the various strategies, $CO_2$ capture emerges as a promising method This technique holds promise in efficiently reducing $CO_2$ levels and thus plays a pivotal role in mitigating climate change.

Among $CO_2$ capture technologies, the use of adsorbents is one of the most common methods. Within various adsorbents, biochar produced from biomass pyrolysis under an inert atmosphere has garnered significant attention due to its low capital cost [3]. Biochar is a permeable carbon-rich solid substance formed by subjecting organic material to thermochemical conversion under oxygen-free conditions [4]. Biochar derived from biomass is an environmentally friendly adsorbent, and its economic feasibility is comparatively enhanced by the fact that it can be produced from waste materials. Additionally, it is considered a viable technology in terms of waste valorization from an environmental perspective.

Studies are being conducted to enhance the $CO_2$ adsorption of biochar by using various biomass sources/wastes or by producing biochar modifications through additional processes. Some of these sources include rice husk, crop residues, sawdust, crustacean shells, coconut waste, and sewage sludge. Post-processing techniques like amine, nitrogen, and phosphorus doping or ionic liquid impregnation are also applied [5-12].

It is stated by Guo et al. (2022) that activation processes need to be applied to biochar produced through pyrolysis for its utilization as an adsorbent [13]. While positive outcomes have been reported post-activation in various studies, it remains an active area of research. This study aims to provide a comprehensive perspective on the production of high $CO_2$ adsorption capacity adsorbents from biomass, systematically evaluate various methodologies employed in the literature, and describe the direction of research in this field. Fundamental data such as authors, affiliations, countries, and research areas have been presented and datasets have been compiled. To analyze a substantial body of published research, the bibliometric analysis method, which utilizes mathematical and statistical techniques has been employed [14-15]. Despite similar bibliometric analysis studies conducted by Laude (2019), Ritchie and Tsalaporta (2022), and Naseer et al. (2022), these studies have focused on general carbon capture technologies or emissions in bioenergy plants [16-18]. In more specific bibliometric analysis studies, materials such as microalgae and silica-based aerogels have been examined [19-21]. This analysis, unprecedented in the relevant field, will enable tracking of statistical new trends for biomass-based adsorbents and identification of the most effective production methods, thereby providing valuable insights to scientists engaged in this research area.

## 2. Material and Methods

The bibliometric analysis approach was initiated with the selection of two important keywords, namely “$CO_2$ capture” and “biomass”. In this study, WoS, currently one of the most widely used multidisciplinary databases with comprehensive citation indexes, and wide range of journals, was employed [22-24]. Performance analysis and scientific mapping analysis were applied to analyze the scientific literature related to biomass-based $CO_2$ capture.

On February 14, 2024, a systematic comprehensive search was conducted in the WoS database for all publications registered between 1995 and 2024 [25]. This search encompassed titles, abstracts, and keywords, targeting documents associated with "$CO_2$ capture" AND "adsorption," AND "biomass" OR "organic waste." Initially, more than 1500 data were gathered, which were subsequently screened for relevance to this study. After detail screening process, a total of 1417 publications were retained for analysis.

### 2.2 Bibliometric Analysis

This article has employed bibliometric analysis to investigate the concept of biomass in the framework of $CO_2$ capture as a source of knowledge. Utilizing bibliometric analysis has enabled a thorough exploration of the evolution of the $CO_2$ capture field, identifying major contributors, emerging research areas, and guiding future research directions. To facilitate data analysis, the following research questions (RQ) have been posed.

- RQ1: How has the publication evolved per year?
- RQ2: What are the document categories?
- RQ3: What are the top 5 WoS categories?
- RQ4: What is the distribution of the number of publications per country?
- RQ5: What are the most published journals?
- RQ6: What are the top 5 institutions who works in this field?
- RQ7: Who are the researchers with the most publications?
- RQ8: What are the most used keywords and research trends?

The bibliometric analysis, conducted to address these questions, commenced with data extraction from the WoS database. Initially, the analysis and citation reports were reviewed, offering essential data such as annual publication volume, h-index, country of origin, journals, institutional affiliations, authorship details, and keywords. Subsequently, this dataset was transferred to Microsoft Excel 365 for more detailed analysis. To facilitate visualization of the results, it was uploaded into the VOSviewer tool. This software relies on bibliographic archives extracted from specific databases and enables a comprehensive analysis of scientific relationships and thematic associations within the collected literature [26-27]. Throughout this research process, networks of co-authors, frequently used keyword, and citation networks of cited authors were generated and visualized to delineate domains.

## 1. Results and Discussion

### 3.1 Publication history and distribution

The foundation for $CO_2$ capture research was laid in the early 1990s, with initial studies focusing on fundamental principles and potential capture methods. Figure 1 illustrates the annual publication distribution from 1991 to 2024, with a total of 29,904 publications recorded to date. $CO_2$ capture research peaked in 2011, driven by increased global awareness of climate change and enhanced funding for sustainable technologies. Since 2018, the number of annual publications on $CO_2$ capture has consistently exceeded 2000.

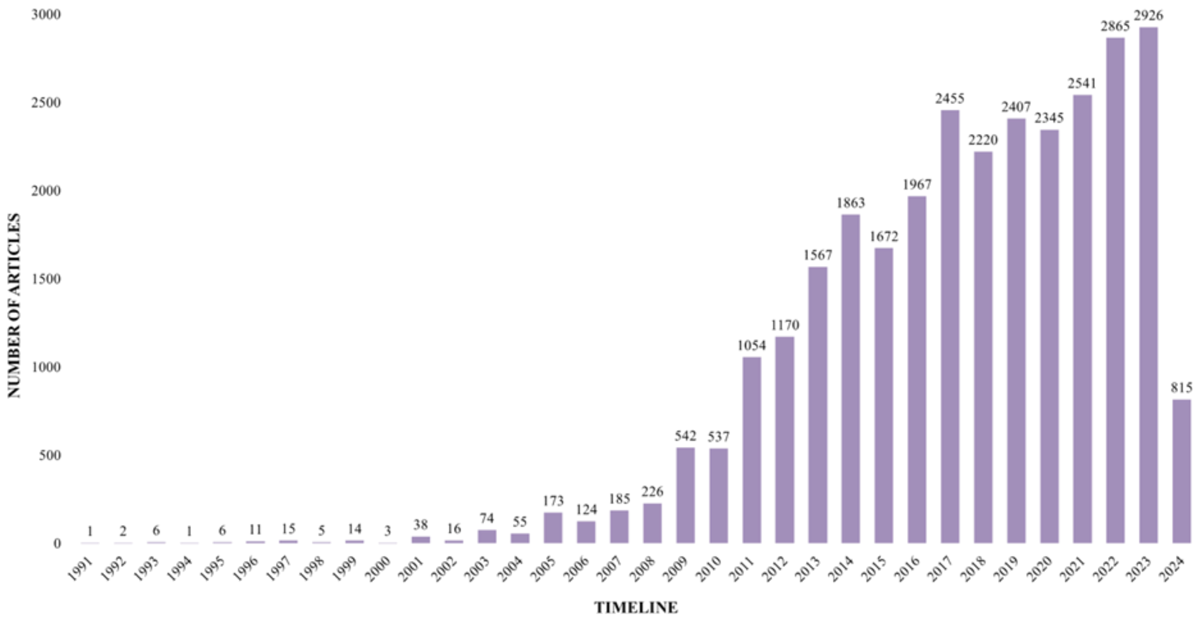


**Figure 1.** Publication distribution in years about CO2 capture

Fifteen years after the commencement of $CO_2$ capture studies, research began to intensify on the development of adsorption techniques [28]. Research output peaked in 2011 (Figure 2a). According to WoS data approximately 30% of these studies focusing on biomass-based adsorbents and the first article on $CO_2$ capture using biomass as an adsorbent was published in 1995, presenting it as an alternative to fossil fuels [29].

In 2009, research on the activation of biomass as a $CO_2$ adsorbent began, laying the groundwork for subsequent studies [30-31]. Within a few years, research expanded to include the use of biomass for $CO_2$ capture in hydrogen production [32]. During the same period, the use of calcium oxide-based adsorbents marked significant progress in carbon capture technologies [33]. Calcium oxide, or quicklime, captures $CO_2$ through carbonation, forming calcium carbonate and effectively sequestering $CO_2$. This methodology led to an increased focus on calcination and $CO_2$ capture studies [34].

The rise in research underscored the importance of biomass activation, leading to extensive studies on the surface area, morphology, and kinetics of various raw materials[35].As shown in

Figure 2b, 2023 saw the highest number of publications, indicating that $CO_2$ capture remains a rapidly evolving and critical area requiring further investigation.

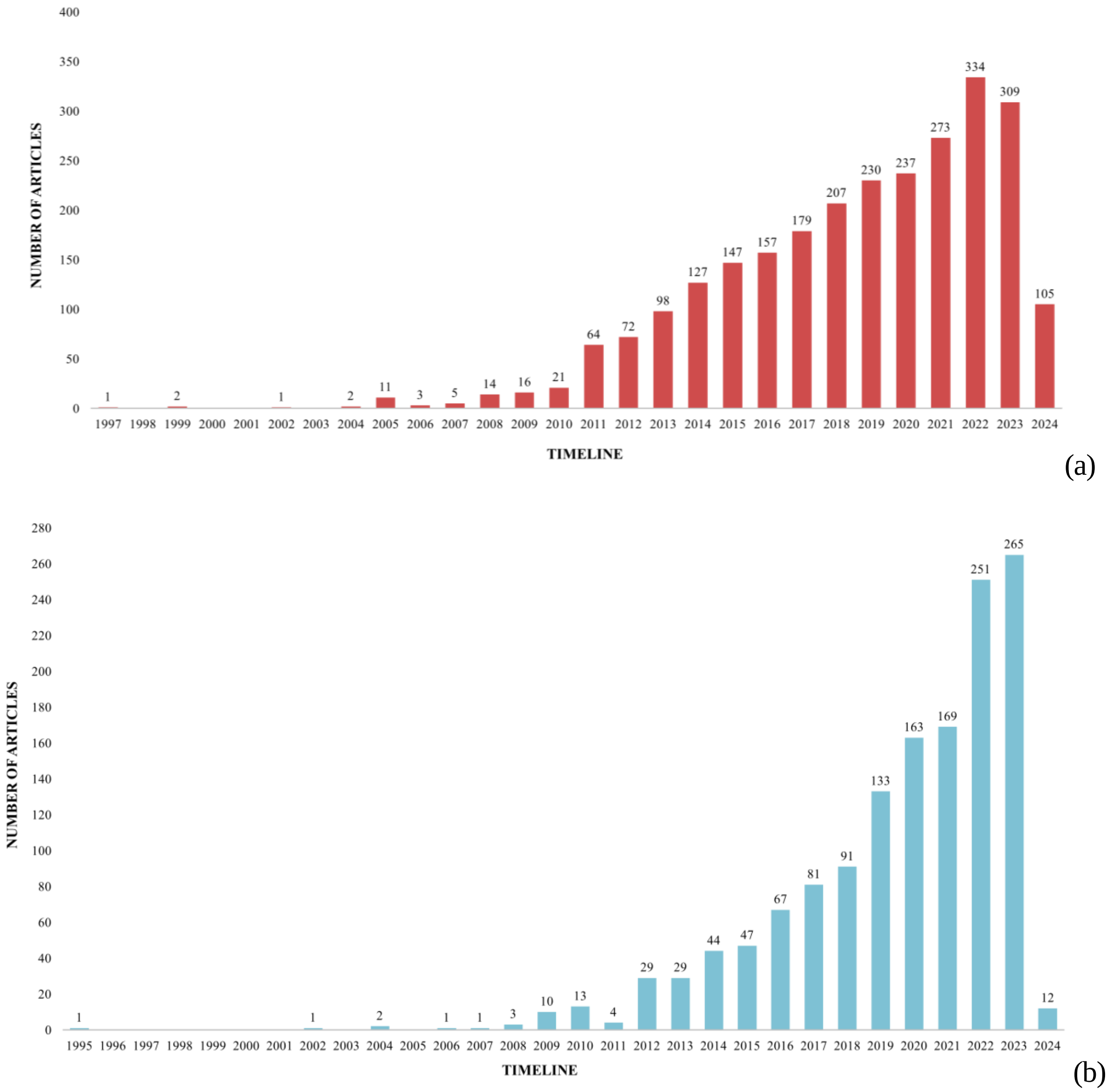


**Figure 2.** Publication distribution per year for CO2 capture with adsorption (a) and with biomass-based adsorption (b)

### 3.2 Document and subject category distribution

An analysis of the documents reveals that 87% (1231) were published as total articles, with 38% (540) classified as early access publications at the time. Among the publications included in the review, 152 (approximately 10%) were review articles. Additionally, other document types, such as proceeding papers and book chapters, was recorded at approximately 8% and 5%, respectively. A notable finding from the review is that 419 of these documents are open access, and as shown in Figure 3, the number of such publications has rapidly increased in recent years.

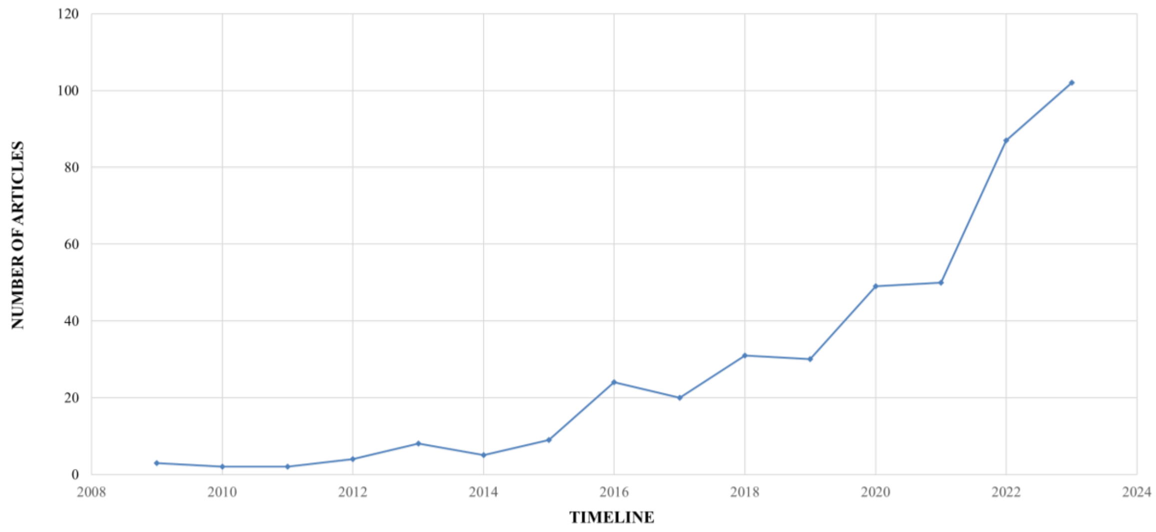


**Figure 3.** Distribution of open access publications per year

When examining the distribution of subject categories, it is observed that the publications encompass approximately 250 subject areas within the WoS categories. The top 5 most utilized categories are shown in Figure 4. The publications are predominantly categorized under Chemical Engineering at 41.5%, followed by Energy Fuels at 27.0%. Additionally, 18.7% and 17.3% of all publications fall under Chemistry Multidisciplinary and Environmental Engineering, respectively. The least utilized categories for this subject are Electrochemistry, Polymer Science, Inorganic Chemistry, Nuclear, Metallurgical Engineering, and Electrical Electronic Engineering.

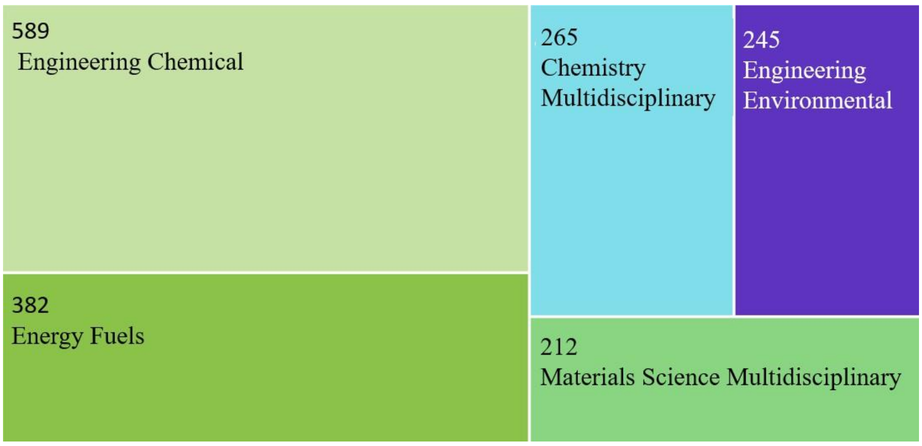


**Figure 4.** The top 5 most utilized WoS categories

### 3.3 Leading journals

A total of 315 publication titles were identified during the analysis. Table 1 presents the number of documents, citations, and JCI Quartile data for all top 5 journals. As shown in table, they are at the Q1 level. The leading journal in the field, the Chemical Engineering Journal, maintains its leadership not only in terms of the number of publications but also in citation impact.

Additionally, the citation relationships of the journals, as obtained from VOSviewer, are also shown in Figure 5.

**Table 1.** Top 5 journals and publication data in the field

| Publication Source Name | WOS Documents | Times Cited | JCI Quartile |
|---|---|---|---|
| CHEMICAL ENGINEERING JOURNAL | 86 | 5381 | Q1 |
| JOURNAL OF ENVIRONMENTAL CHEMICAL ENGINEERING | 49 | 1183 | Q1 |
| JOURNAL OF CO2 UTILIZATION | 49 | 1872 | Q1 |
| FUEL | 49 | 2034 | Q1 |
| SEPARATION AND PURIFICATION TECHNOLOGY | 43 | 760 | Q1 |

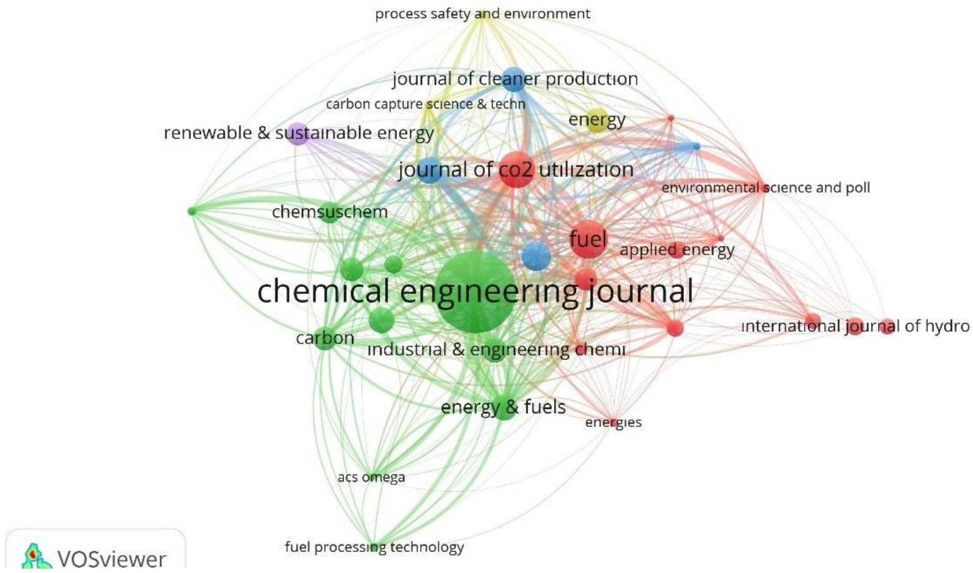


**Figure 5.** The map of the journal relationship according to citations

### 3.4 Contributing countries and institutions

Research on $CO_2$ capture using biomass-based adsorbents has been conducted by a total of 79 countries. The publication counts, citations, international collaborations, and the number publications in top 10% for the top ten contributing countries are summarized in Table 2. China significantly leads in this field, accounting for 42% of all publications worldwide. China is followed by the United States, the United Kingdom, Spain, and South Korea. Due to a recent name change, Türkiye is listed twice, but collectively, it constitutes 2% of all documents and does not rank among the top 10 countries.

China also stands out with a total of 22.262 citations, making it one of the leading countries in this field. Although Germany ranks 10th in terms of the number of publications, it has a remarkably high number of publications in top 10% compared to other countries. Nearly half of its articles are distinguished as high-quality publications, giving Germany a significant advantage in terms of citation impact.

**Table 2.** Top 10 countries and publication data in the field

| Country | Documents | Times Cited | International Collaborations | % Documents in Top 10% | Hot Papers |
|---|---|---|---|---|---|
| China | 604 | 22,262 | 174 | 29.47% | 2 |
| USA | 149 | 13,835 | 99 | 37.58% | 0 |
| United Kingdom | 103 | 5,561 | 74 | 28.16% | 0 |
| Spain | 102 | 4,296 | 59 | 32.35% | 0 |
| Malaysia | 84 | 2,997 | 47 | 20.24% | 0 |
| South Korea | 74 | 3,063 | 43 | 24.32% | 0 |
| England | 70 | 4,71 | 48 | 32.86% | 0 |
| Australia | 59 | 4,497 | 36 | 25.42% | 0 |
| Saudi Arabia | 32 | 2,618 | 26 | 28.12% | 0 |
| Germany | 19 | 2,924 | 15 | 47.37% | 0 |

The international collaborations of the publications were also examined using VOSviewer. In VOSviewer, countries were filtered based on a minimum of 10 publications and 5 citations, and the results were evaluated. Within this scope, 36 interesting countries were identified such as Argentina, Vietnam, Egypt etc. (Figure 6). It was observed that China, the highest publishing country, has collaborations with many countries, while Türkiye has also been found to collaborate with different countries such as Norway, Germany, Egypt, Sweden, Spain, South Korea, Indonesia and Canada.

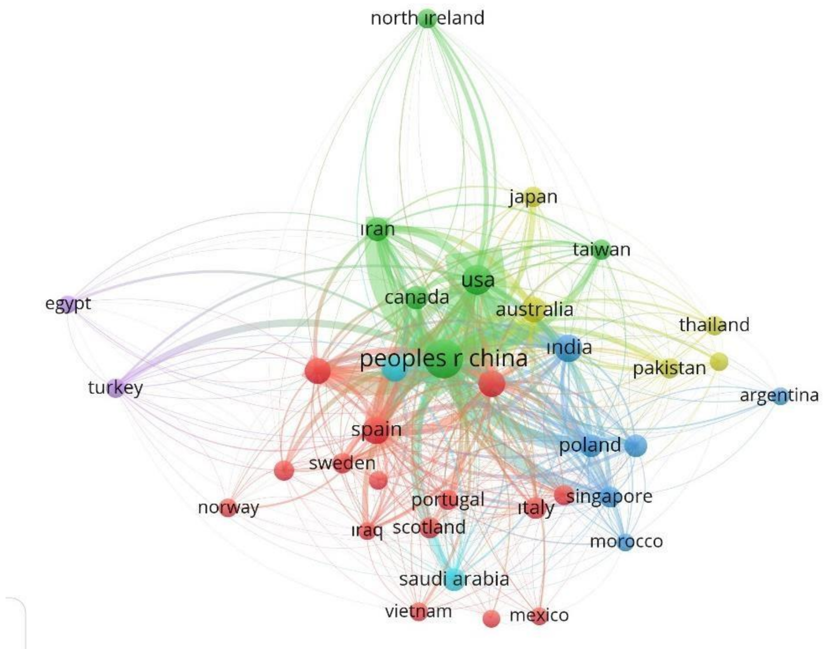


**Figure 6.** The map of significant country collaboration about biomass-based $CO_2$ adsorption topic

Similar to the extensive relationships between countries, a total of 1.359 institutions have contributed to research on this topic, demonstrating a widespread collaborative effort.

Numerous contributions have been recorded from academic institutions, research laboratories, government agencies, and industry partners worldwide. The top 5 leading institutions in this field are presented comparatively in the figure.

In Türkiye, the top five institutions working on this topic are led by Osmaniye Korkut Ata University with 8 articles. This is followed by Marmara University (3 articles), Konya Technical University (3 articles), Hitit University (3 articles), and Hacettepe University (2 articles).

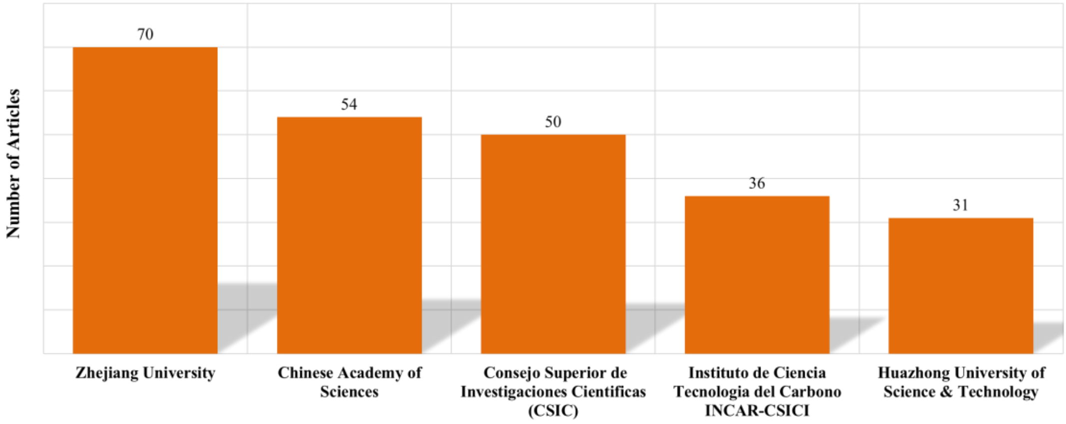


**Figure 7.** The top 5 leading institutions working on related topic

### 3.5 Researchers

A total of 5.254 researchers have collaborated on biomass-based $CO_2$ adsorbents.

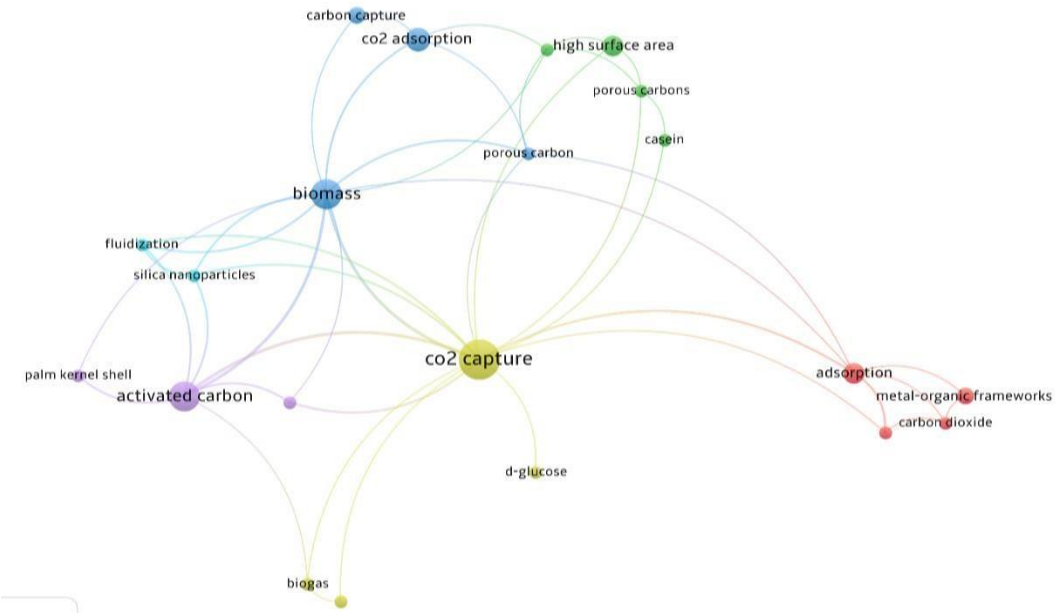


**Figure 8.** Top 5 Researchers' fields of publications by keywords

**Table 3.** 10 contributing researchers and its information in the field

| Person Name | WoS Documents | Times Cited | Affiliation | Country or Region |
|---|---|---|---|---|
| Cova Pevida | 35 | 1.531 | Consejo Superior de Investigaciones Cientificas (CSIC) | SPAIN |
| Fernando Rubiera | 29 | 1.436 | Consejo Superior de Investigaciones Cientificas (CSIC) | SPAIN |
| Suzana Yusup | 20 | 777 | TNB Res Sdn Bhd | MALAYSIA |
| Huabin Xing | 19 | 860 | Zhejiang University | CHINA |
| Xin Hu | 19 | 1.584 | Zhejiang Normal University | CHINA |
| Xili Cui | 16 | 713 | Zhejiang University | CHINA |
| Zongbi Bao | 15 | 820 | Zhejiang University | CHINA |
| Yao Shi | 14 | 557 | Yangzhou University | CHINA |
| Ajayan Vinu | 14 | 537 | University of Newcastle | AUSTRALIA |
| Yi He | 13 | 499 | University of Washington | USA |
| MARÍA V GIL | 13 | 506 | Universidad de Leon | SPAIN |

Cova Pevida, a chemical engineer at Instituto de Ciencia y Tecnología del Carbono (Spain), is a leading researcher in the field with 35 publications. Fernando Rubiera, also working at the same institution alongside Dr. Pevida, ranks second and focuses on the development and optimization of biomass-based adsorbents, particularly activated carbon and biochar. They have published numerous articles detailing the synthesis, characterization, and performance evaluation of these adsorbents for $CO_2$ capture applications. Their work demonstrates that the adsorbents they developed are viable alternatives to traditional adsorbents. On the other hand, Suzana Yusup, a chemical engineer in Malaysia, is noted for having the highest collaboration rate with 45% of all documents, according to WoS Incites data.

An analysis of the keywords from the top 5 researchers' publications in this field is presented in Figure 8. The results indicate that these researchers conduct experimental studies focusing on the properties of adsorbents. Various modifications have been applied to biomass to enhance surface area and improve $CO_2$ adsorption capacity. This emphasis on experimental research and material optimization highlights their significant contributions to advancing the understanding and effectiveness of biomass-based $CO_2$ capture technologies. It is also observed that many of these studies are conducted on a laboratory scale, suggesting that future research should be directed towards technological advancements and developments.

### 3.6 Research Trends and Future Outlook

Researchers can identify emerging trends, popular research topics, and areas of interest by analyzing frequently used keywords in academic publications. Keyword analysis has been utilized to understand the core themes and topics of studies on biomass-based $CO_2$ adsorbents. In this keyword analysis, a total of 2.836 keywords were identified. To enhance clarity and readability, the analysis was refined to highlight the most frequently occurring keywords, resulting in the visualization of 48 prominent terms (Figure 9). The analysis conducted using VOSviewer revealed "$CO_2$ capture" as the most frequently used keyword, underscoring its central importance in the discourse on biomass-based $CO_2$ capture. This was closely followed by keywords such as "adsorption," "porous carbon," "carbon dioxide," and "biochar," emphasizing the fundamental concepts and methodologies relevant to this research area.

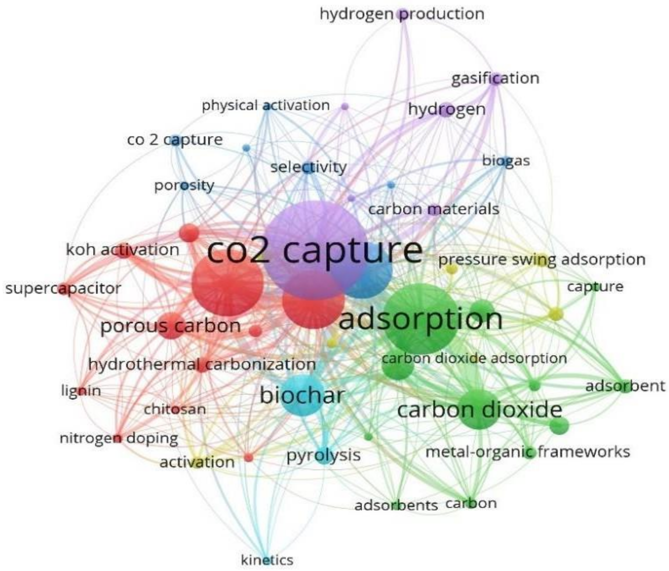


**Figure 9.** The map of utilized keywords co-network in publications on biomass-based $CO_2$ capture.

Notably, the prominence of the keyword "activation" highlights this process as an intensively studied and effective strategy for enhancing the $CO_2$ adsorption capacity of biochar. Activation processes, such as chemical or physical activation, are essential for modifying the surface properties and pore structure of biochar to optimize adsorption performance [2] In addition to the significant keywords identified, it is noteworthy that studies on kinetics and selectivity are actively being conducted within this research scope. These studies focus on understanding the rate of $CO_2$ molecules captured and the degree to which the adsorbent selectively binds $CO_2$ over other gases present in the related environment. Understanding the selectivity of adsorbents is crucial for material design, serving as a key point for those aiming to develop materials with higher adsorption capacities.

The keyword analysis also yielded some interesting insights. Keywords such as "calcination," "supercapacitor," and "$SO_2$ adsorption," while not traditionally associated with $CO_2$ capture, emerged in the analysis. This indicates that materials in this research area are being integrated into various technologies, highlighting the significance of developments in this field.

In last 5 years; significant advancements have been made for the development of biomass-based adsorbents for $CO_2$ capture, with the need for sustainable and cost-effective solutions to mitigate carbon emissions. Microalgal biomass has emerged as a promising candidate due to its high surface area and porosity, which enhance its $CO_2$ adsorption capabilities [36]. Nitrogen-doped carbon materials, including cellulose nanofibers and aerogel fibers, have also shown considerable potential. These materials, derived from plant-based sources, offer high surface areas and enhanced $CO_2$ adsorption capacities due to the presence of nitrogen functionalities [37].

Graphene-based biomass is another innovative approach, incorporating graphene to provide a high surface area and strong interaction sites for $CO_2$ molecules, thereby improving adsorption efficiency [37] Calcium-based adsorbents utilize calcium compounds to enhance $CO_2$ capture through chemical reactions, forming stable carbonates [34]. Cement-based materials have been explored for their ability to incorporate $CO_2$ capture capabilities, leveraging their widespread availability and stability [38]. Nanoporous organic polymers represent another promising material, and they have high surface areas and tunable pore sizes, making them highly effective for selective $CO_2$ adsorption [39].

Studies are being conducted to enhance the $CO_2$ adsorption of biochar by using various biomass sources or by producing biochar modifications through additional processes, thereby achieving high adsorption capacity and selectivity. Amine-functionalized biochar from desiccated coconut waste achieved a high adsorption capacity of 61.78 mg/g (~1,4 mmol/g) [6]. Biochar impregnated with ionic liquids improved $CO_2$ adsorption capacity, kinetics, and selectivity by 4-90% compared to bulk adsorbents, and doubling its capacity under increased pressure [7]. Waste crustacean shells-based biochar fixed 225.02 mg $CO_2$ per g at 50°C and 0.2 bar (Sun et al. 2024). Phosphorus-doped biochar showed 1.34 mmol/g $CO_2$ adsorption at 72°C and 1 bar [9]. Nitrogen-doped biochar modified with $H_2O_2$ showed high adsorption of 5-8 mmol/g and superior selectivity [11]. Biochar from a type of sawdust activated with KOH achieved 5.79 mmol/g at 0°C and 750 mmHg due to high microporosity [40]. Additionally, agro waste-derived activated carbon showed an adsorption capacity of 5.225 mmol/g [12].

## 2. Conclusion

In conclusion, this article elucidates the promising prospects and evolution of biomass-based $CO_2$ capture technologies through a bibliometric analysis encompassing keywords, leading organizations, research, and journals, and how these parameters have evolved over the years.

Research in $CO_2$ capture with biomass-based adsorbents has experienced notable growth worldwide due to the push for greener, more sustainable practices and the urgent need to mitigate $CO_2$ emissions. Notably, the year 2023 marked a significant increase, with the highest number of published documents reaching 263.

Out of the 1.417 articles selected for analysis, the majority, comprising 1.231 articles, are research articles, indicating a substantial focus on primary research in this field. Open access article numbers are increasing year by year.

The analysis of subject categories in the WoS database reveals that most publications are primarily classified under Chemical Engineering, followed by Energy Fuels, Multidisciplinary Chemistry, and Environmental Engineering.

Numerous keywords help us understand the trends in this field. Activation and adsorbent characteristics continue to be investigated to increase adsorption capacity.

The field should be characterized by active research, pilot projects, and growing interest from industry. However, challenges related to scalability, efficiency, and economic viability need to be addressed to achieve widespread commercial adoption. Continued innovation and supportive policies will be also crucial in advancing these technologies. Despite these challenges, there has been a notable surge in the development of biomass-based adsorbents over the last five years. These advancements include materials such as microalgal biomass, nitrogen-doped carbon materials, cellulose nanofibers, aerogel fibers, graphene-based biomass, calcium-based adsorbents, cement-based materials, CaO microspheres, and nanoporous organic polymers. These innovative materials hold promise for enhancing $CO_2$ capture capabilities through modifications aimed at increasing surface area and improving adsorption capacity.

## Ethics in Publishing

There are no ethical issues regarding the publication of this study.

## Author Contributions

Ozben KUTLU conceived of the presented idea, managed, revised and edited all the manuscript. Yagmur OLGUN collected data, checked whole publications according to topic, and created the figures and tables by VOSviewer or other software’s. All authors discussed the results and contributed to the final manuscript.

## Acknowledgements

This article was conducted as part of a master's thesis and received no financial support.

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