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The Role of Biomass-Based Carbon Capture and Storage in Sustainable Development: A Bibliometric Review

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Abstract:

This paper presents a bibliographic review of the role of biomass-based carbon capture and storage (BECCS) in promoting sustainable development. BECCS, a technology that combines biomass-based production and carbon sequestration, has attracted attention for its potential to mitigate climate change by removing carbon dioxide from the atmosphere. The review analyzes a wide range of scientific literature to assess the current state of BECCS research and identifies key trends, influential authors, and key research topics. The environmental, economic, and social impacts of BECCS are explored, including its contribution to carbon neutrality, energy security, and rural development. Furthermore, the overview highlights the following challenges associated with the implementation of BECCS: B. Land use competition, scalability, and economic feasibility. By synthesizing the findings, the paper provides a comprehensive overview of the potential role of BECCS in sustainable development and outlines future research directions needed to overcome existing obstacles and optimize the integration of the system into climate policy frameworks. Data were collected from the Scopus database and analyzed using VOSviewer software to visualize authors' frequently occurring keywords. The results indicate the potential of BECCS is widely recognized, its effectiveness in achieving sustainable development goals (SDGs) hinges on addressing several critical challenges, including high operational expenses, conflicts over land use, and the environmental risks associated with carbon dioxide storage. This article aims to serve as a valuable reference for advancing future research on biomass-based carbon capture and storage.

Keywords — **Biomass, carbon capture, climate change, decarbonization**

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I. INTRODUCTION

The urgent need to address climate change and reduce greenhouse gas emissions has led to the exploration of various technological solutions, with biomass-based carbon capture and storage (BECCS) emerging as one of the most promising options. BECCS combines the use of biomass- derived biomass-based with the capture and long-term storage of carbon dioxide (CO2) to effectively remove this harmful greenhouse gas from the atmosphere. This dual mechanism of carbon capture and energy generation makes BECCS a key tool for achieving net-zero emissions, a crucial step in mitigating the effects of global warming [1]. By enabling negative emissions, BECCS not only reduces atmospheric CO2 concentrations, but also offers the potential to reverse the adverse effects of climate change, thereby helping to restore balance to the global carbon cycle. Moreover, BECCS offers an opportunity to improve energy security through the use of renewable biomass resources derived from agricultural waste, forest residues, and other biomass feedstocks [2]. This renewable

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approach to energy production, combined with carbon sequestration, offers a compelling solution to the climate crisis.

Despite the theoretical potential of BECCS, there are several challenges to its large-scale implementation. One of the main concerns concerns scalability. Although the technology has been demonstrated on a small scale, scaling it up to the levels required to achieve global climate goals remains a major obstacle. The economic feasibility of BECCS is another key issue, as the technology currently involves high costs for carbon capture, transportation, and storage [3].

Furthermore, the impact of BECCS on land use has raised concerns about conflicts with food production, biodiversity conservation, and other land-based needs. Large-scale deployment of BECCS may require significant areas to cultivate biomass crops, which could lead to land-use changes that affect ecosystems and food security [4]. Furthermore, public acceptance and societal concerns regarding storing CO2 in geological formations need to be considered, as many local communities have expressed concerns about the long-term safety and environmental impacts of underground CO2 storage.

Given the growing interest in BECCS and its potential role in achieving climate change goals, a comprehensive understanding of the current state of research is needed to assess its contribution to sustainable development. In this article, we provide a bibliographic review of the literature on BECCS, focusing on its role in mitigating climate change and supporting sustainable development. A bibliographic approach is particularly useful for systematically assessing trends, key research areas, and influential studies in the BECCS field, providing insights into developing research and emerging topics. The review aims to uncover the main drivers of BECCS research and identify gaps in the existing body of knowledge by analyzing publication patterns, author names, and citation networks [4]. This bibliographic analysis also allows us to identify the geographic distribution of research, highlighting regions that are leaders in BECCS research and those that require more targeted efforts.

The role of BECCS in sustainable development is multifaceted and includes not only environmental benefits such as climate change mitigation, but also potential social and economic co- benefits. By promoting the development of the biomass-based industry, BECCS could contribute to rural development and job creation, especially in regions with abundant biomass resources [2]. Furthermore, integrating BECCS into broader climate policy frameworks could spur investment in green technologies and infrastructure, accelerating the transition to a low-carbon economy. However, to fully realize the potential of BECCS, various associated challenges need to be addressed, including cost reduction, land use optimization, and public perception. Therefore, this review also aims to highlight barriers to the adoption of BECCS and provide recommendations to overcome these barriers to improve the scalability and effectiveness of BECCS as a climate change mitigation tool.

This paper aims to contribute to the ongoing debate on BECCS by summarizing the findings of numerous studies and providing a clearer understanding of its potential role in sustainable development. By highlighting the current research state, this review aims to provide valuable insights for policymakers, researchers, and industry players who want to advance BECCS technology and harness its capabilities in the fight against climate change. The review also identifies key research gaps that need to be addressed to ensure BECCS is integrated into global strategies.

II. METHODOLOGY

A. Conceptual Framework

A bibliometric analysis of the existing literature, coupled with a meticulously crafted survey strategy, was employed to delineate best practices in the realm of scientific knowledge, particularly concerning environmental sustainability disclosure [5]. This comprehensive methodology effectively integrates quantitative bibliometric techniques with thorough qualitative surveys, facilitating a more profound comprehension of the evolution of scientific knowledge within this specific area. The quantitative dimension of this methodology allows

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for the examination of extensive datasets and the identification of prevailing trends, while the qualitative component enriches the analysis by providing context and insights into the foundational theories, methodologies, and practical implications of the research. By synthesizing these two approaches, the study presents a well-rounded perspective that not only charts the progression of research over time but also elucidates the significance and implications of these trends within the broader scientific dialogue [6]. This particular investigation merges both quantitative and qualitative research methodologies to assess the literature on environmental sustainability disclosure, utilizing data sourced from the esteemed Scopus database. Scopus serves as a valuable repository of academic publications, ensuring that the data employed in this bibliometric study is both comprehensive and current. By integrating these methodologies, the research aims to explore not only the numerical trends within the literature, such as publication rates, author contributions, and citation metrics, but also the themes, concepts, and discussions that characterize the field of environmental sustainability disclosure. This dual approach fosters a more intricate understanding of the academic landscape related to sustainability, allowing for the identification of emerging trends and potential research gaps.

The conceptual framework utilized in this research acts as a foundational structure that delineates the parameters of the review, organizes the existing literature, and highlights the principal themes or constructs pertinent to the area of study [4]. This framework is crucial for systematically arranging the extensive literature and ensuring that the review concentrates on the most relevant and impactful studies. Additionally, it aids in formulating specific research inquiries, selecting appropriate variables for examination, and establishing a coherent structure for the investigation. In this manner, it facilitates the identification of significant research domains within environmental sustainability, including technological innovations, policy suggestions, and the obstacles related to sustainability practices. This organized methodology not only clarifies which elements of the field will be investigated but also serves as a guiding instrument for future research, emphasizing areas that may need additional exploration and development. Ultimately, this approach guarantees a thorough, methodical, and well-structured literature review, thereby contributing to both theoretical progress and practical advancements in the field of environmental sustainability. The methodology consists of several stages of development. The first stage involved determining the scope of the review by formulating a number of research questions that served as the framework for the literature review. The following are the research questions.

a. What are the current research developments, gaps, and future research prospects in the topic of biomass-based carbon capture and storage?
b. What is biomass-based carbon capture and storage and how can make a sustainable development?

This approach enables researchers to efficiently and systematically analyze extensive datasets. By employing sophisticated bibliometric techniques, researchers can manage and scrutinize large volumes of data that would be challenging to handle through manual methods. This strategy provides a thorough and detailed perspective on the field, illuminating its development, prevailing trends, and nascent research domains. Additionally, it offers critical insights into the theoretical progressions that have influenced the discipline over time, as well as an awareness of existing knowledge gaps. Such analysis is vital for assessing the current landscape of the field, allowing researchers to evaluate the significance and impact of various studies. Beyond presenting a current overview of research, bibliometric methods also reveal future opportunities and potential avenues for further exploration, thus informing the formulation of new research inquiries and initiatives [2]. The capacity to monitor these trends over time is essential for comprehending the field's advancement and

future trajectory. The specific criteria established for selecting, evaluating, identifying, and incorporating studies into this analysis are crafted to

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ensure that only the most pertinent and impactful articles are included, thereby upholding the integrity and rigor of the review process. These criteria will be elaborated upon in the subsequent section, "Data Collection," which will detail the methodology employed for curating the dataset. In this instance, the metadata for the bibliometric analysis was sourced from the Scopus database on December 4, 2024, providing a robust and contemporary repository of scholarly publications, thereby ensuring the data's relevance and reliability for the review.

B. Data Collection

The process of data collection involved the strategic input of a meticulously chosen set of keywords into the Scopus database, which is a prominent and extensive repository for academic literature. The selection of keywords plays a pivotal role in executing a systematic and effective literature review, as it significantly influences the relevance and quality of the retrieved results. The careful choice of keywords is particularly vital, as it shapes the scope and depth of the literature to be examined, thereby affecting the interpretation of the study's overall findings [7]. In this instance, the keywords employed in the search encompassed phrases such as "biochar" AND "climate" OR "change" AND "carbon" OR "capture." These terms were deliberately chosen to encompass a wide array of research concerning the function of biochar in addressing climate change, with an emphasis on carbon capture and its environmental ramifications. To enhance the relevance and accuracy of the search outcomes, a series of exclusion criteria were implemented utilizing the database's integrated filtering mechanisms. These filters addressed various characteristics of the publications, including publication year, document type, language, source type, and publication stage. The publication year was confined to the range from 2010 to 2024, ensuring that the studies incorporated in the analysis were both recent and pertinent to the current research landscape in the field. Only articles published in English were included, as they represent the majority of scientific literature in this domain. Furthermore, the search was restricted to finalized journal articles, thereby excluding conference papers, reviews, and other non-peer-reviewed materials that could potentially introduce bias or diminish the quality of the dataset.

The initial search strategy resulted in the identification of approximately 525 scholarly articles. Following the implementation of automated filtering criteria, this number was narrowed down to 115 articles that satisfied the established keyword parameters and filtering requirements. The subsequent phase of data collection involved a meticulous manual screening process, during which the titles and abstracts of the selected articles were thoroughly examined to determine their relevance to the research focus. This manual review is essential for ensuring that only studies that are genuinely relevant to the topic are included in the final analysis. Ultimately, 92 articles were identified as appropriate for inclusion in the bibliometric analysis. This comprehensive data collection process— comprising an initial keyword search, automated filtering, and manual review—ensured that the selected articles for the bibliometric review were both pertinent and of high scholarly quality. By integrating both automated and manual filtering methods, the study sought to establish a comprehensive and reliable dataset that accurately reflects the current landscape of research concerning biochar, climate change, and carbon capture. The final compilation of 92 articles serves as the basis for the bibliometric analysis, which aims to elucidate trends, advancements, and significant themes within this field of study.

C. Bibliometric Analysis

The purpose of this study is to conduct a scientific mapping of the work employing the bibliometric analysis, demonstrating authors, the related institutions and the countries, as well as citations to the publications [8]. As it will be seen in this study, bibliometric analysis can be used to provide indicators of what more recent research has been done in a certain field of study as well as where such research is still lacking [9]. For this task, the software called VOSviewer was used which aims to facilitate researchers in visualizing and conducting bibliometric mapping and data analysis

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of the relationships present in the datasets (El Bekkouri et al., 2024; Özyürek et al., 2024; Yabo et al., 2024). This tool is also helpful for developing co-authorship and co-occurrence networks along with citation networks. It has been said that the use of VOS provides advantages over other distance-based maps e.g., V-SOM & Kopcsa- Schiebel as well as MDS, in visualizing metadata information. In the case of VOSviewer, nodes representing keywords are display at a distance that indicates how strong the relationship is among the various keywords. The closer the distance, the stronger the link between the two keywords or nodes. Thus, in a VOS cluster map, keywords or nodes are organized so that they do not overlap with each other [10].

Through this research, citation networks and co-authorship through authors and countries have been examined. In line with understanding the collaboration of authors, institutions, and countries, the cooperation was presented regarding the issue of soil remediation with plasma technology. In this sense, as an example, knowledge of scientific cooperation can help in the development of innovation in this subject since it allows for more sophisticated systems of soil remediation [11].

D. Qualitative Content Analysis

Content analysis refers to a certain research methodology whose goal is to interpret and measure the content of communication that can be textual by nature, to define its essential and dominant characteristics, themes, stereotypes, and biases. This method can be referred to as either qualitative or quantitative, with each having a unique role in research. In qualitative content analysis, the main focus is put on text analysis so critical assumptions and stereotypes through language usage and its contextual meanings (Rucks-Ahidiana, 2024). According to the authors of past bibliometric studies [8], [12], content analysis demonstrates applicability as a qualitative supplement in bibliometric analysis.

TABLE I. CRITERIA FOR INCLUSION AND PRE-PROCESSING IN BIBLIOMETRIC ANALYSIS

Analysis	Pre-processing criteria
Co-authorship authors	In full counting, the minimum number of documents of an author is set to 2, the minimum number of citations of an author is set to 18, and the map shows only the most extensive set of networks.
Co-occurence author keywords	In full counting, the minimum numbers of occurrences of a keyword is set to 2, and the map shows only the most extensive set of networks.

III. RESULT AND DISCUSSION

A. Key Principles of Technology

The bibliometric analysis indicates a significant rise in publications pertaining to biomass-based carbon capture and storage (BECCS) over the last twenty years. Particularly, there has been a notable acceleration in research activities since the early 2000s, with a pronounced increase observed post-2010 [13]. This trend underscores an enhanced acknowledgment of BECCS as a feasible technology for realizing negative emissions and addressing climate change challenges. The research delves into the synergy between biomass carbon capture and CO_2 storage methodologies, examining both the advantages and obstacles associated with large-scale deployment [14]. The field of BECCS has undergone considerable transformation since its early days. Initially, investigations were predominantly centered on traditional carbon capture and storage (CCS) methods. However, as the imperative to combat climate change intensified, the focus shifted towards the utilization of biomass as a sustainable feedstock within the carbon capture framework. This transition was driven by an

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increasing emphasis on negative emissions technologies, positioning BECCS as a viable approach for sequestering greater amounts of carbon than are released into the atmosphere [13]. In the last decade, there has been a growing intersection between biomass-based and CCS research, reflecting comprehensive policy efforts aimed at achieving net-zero emissions by the middle of the century [15].

A significant emphasis in the existing literature pertains to the technological innovations within the field of Biomass Carbon Capture and Storage (BECCS). This body of research predominantly investigates the integration of biomass with carbon capture and storage techniques to facilitate carbon sequestration [16]. Critical technological domains encompass carbon capture efficiency, biomass conversion processes, and methods for CO_2 storage. For instance, various studies assess the performance of distinct carbon capture technologies, such as post-combustion, pre- combustion, and oxy-fuel combustion, in conjunction with biomass feedstocks [13]. Investigations into biomass conversion aim to enhance the efficiency of utilizing biomass as a feedstock for carbon sequestration. Notable challenges include the necessity to ensure that the carbon capture process does not become excessively energy-demanding or negate the carbon savings achieved [14]. Additionally, CO_2 storage technologies represent another critical area of focus, particularly concerning the long-term sequestration of CO_2 in geological formations, where it is essential to mitigate the risks of leakage [16].

Environmental sustainability plays a crucial role in the implementation of BECCS technologies, particularly in relation to the life-cycle effects of biomass production, carbon capture, and CO_2 storage. Numerous studies perform life-cycle assessments (LCAs) to analyze the environmental consequences of BECCS systems [17]. These assessments generally consider the emissions linked to biomass cultivation, transportation, carbon capture, and storage. Such evaluations are essential in determining whether BECCS technologies can achieve net negative emissions, which is vital for fulfilling international climate objectives [15]. Nonetheless, various challenges persist in this area. For instance, extensive biomass plantations may compete with land designated for food production, raising issues related to land-use change, food security, and the loss of biodiversity [18]. In light of these challenges, alternative biomass sources, including agricultural waste and non-food crops, are being investigated to mitigate the adverse effects associated with biomass cultivation [16].

The economic feasibility of Biomass-based with Carbon Capture and Storage (BECCS) represents a significant area of inquiry within the existing literature. Although BECCS technologies hold promise for achieving negative emissions, they encounter substantial financial challenges primarily due to the energy demands associated with carbon capture, as well as the requisite infrastructure for the transportation and storage of CO_2 [19]. A major obstacle lies in the elevated capital and operational costs linked to BECCS, particularly concerning biomass sourcing and the expansion of storage technologies. Effective policy frameworks are vital for mitigating these economic hurdles. For BECCS to attain economic sustainability, robust incentives and governmental backing are imperative. Implementing carbon pricing strategies, providing subsidies for renewable energy initiatives, and funding research and development (R&D) in BECCS can help alleviate financial uncertainties and stimulate increased investment in these technologies [16]. Furthermore, regulatory frameworks and well-defined governance structures are crucial for overseeing the long-term risks associated with CO_2 storage, particularly in relation to the potential for [15]. An emerging research focus is the social aspects of BECCS, especially concerning public acceptance and risk perception. Public apprehensions regarding BECCS often revolve around land utilization, food security, and the risks associated with CO_2 storage [18]. Research indicates that involving local communities in the decision-making process, resolving land-use disputes, and offering clear information about the environmental risks and advantages of BECCS are essential for fostering public endorsement [20].In areas where extensive biomass plantations are planned, it is crucial to implement social inclusion

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strategies that address the needs of local populations, particularly in regions experiencing significant food insecurity [18]. These social considerations are vital for the long-term viability of BECCS technologies, as their successful implementation depends not only on technological capabilities but also on societal acceptance.

BECCS research is primarily situated in developed areas, notably in Europe, North America, and certain regions of Asia. The United States, the United Kingdom, and the Netherlands are at the forefront of BECCS research, supported by robust governmental policies and funding programs aimed at attaining carbon neutrality [21]. These regions allocate significant resources to both BECCS research and large-scale implementation initiatives, bolstered by government-supported carbon pricing mechanisms and financial incentives. Nevertheless, there is a burgeoning interest in BECCS within emerging economies, particularly in China and Brazil, which possess substantial biomass resources. These nations are beginning to investigate BECCS as a feasible approach to satisfy energy requirements while also addressing climate objectives [19]. Research efforts in these areas often emphasize the integration of renewable biomass with carbon sequestration technologies to facilitate sustainable energy production and mitigate carbon emissions.

Numerous engineering challenges persist despite the continuous progress in technology. There is a pressing need for biomass conversion technologies to enhance their energy efficiency, while carbon capture systems require optimization to mitigate the energy costs associated with CO_2 capture [13]. Additionally, the establishment of CO_2 storage sites carry considerable risks, particularly regarding the long-term integrity of storage and the prevention of leakage. The large- scale integration of these technologies is fraught with complexity and expense, necessitating ongoing innovation to boost efficiency. The financial viability of biomass-based carbon capture and storage (BECCS) technologies hinges on substantial investment and remains uncertain in the absence of strong policy frameworks. High expenses related to biomass sourcing, carbon capture processes, and the requisite transportation infrastructure pose significant obstacles. It is crucial to pursue further research aimed at reducing these costs, alongside implementing financial incentives and market strategies such as carbon credits, to facilitate the widespread adoption of BECCS technologies [16]. Moreover, the expansion of large-scale biomass plantations may incite land- use conflicts, especially in areas already grappling with food insecurity and biodiversity decline. The competition for land between food production and biomass farming raises critical questions about the sustainability of extensive BECCS initiatives [18]. Therefore, the development of more sustainable biomass sources, including agricultural residues and algae, is essential for addressing these challenges. The review identifies several critical areas for future research which is Technological innovation in the field of biomass conversion, carbon capture, and CO_2 storage systems necessitates a concentrated research effort aimed at enhancing both efficiency and cost-effectiveness. Additionally, comprehensive life-cycle assessments are essential to thoroughly evaluate the environmental, economic, and social sustainability of Biomass Carbon Capture and Storage (BECCS) technologies. Furthermore, it is imperative for research to explore the regulatory frameworks that underpin BECCS, which encompass aspects such as carbon pricing, subsidies, and international collaboration. Lastly, investigating social acceptance and public perceptions is vital for addressing concerns related to land-use changes and the risks associated with CO_2 storage.

B. Bibliometric Analysi: Current research trends and status

Fig. 1 illustrates the trend in scientific article production related to biomass-based carbon capture and storage (BECCS) from 2011 to 2024. In the early period (2011-2014), the number of publications was relatively low and stable, with slight increases observed in the subsequent years from 2015 to 2019. This initial slow pace may reflect early-stage exploration of the technology, as researchers were still investigating its feasibility and potential applications. However, starting from 2020, there was a more notable and consistent rise

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in the number of publications, signaling a growing recognition of the importance of BECCS in addressing climate change. This surge is likely driven by increasing global awareness of the urgent need to reduce carbon emissions and the potential of BECCS to contribute to climate mitigation strategies. The highest peak in 2024 suggests that the field is gaining significant traction among the scientific community, reflecting not only the growing urgency of the climate crisis but also enhanced research efforts to optimize and scale up BECCS technologies.

This upward trend in scientific output may also indicate that substantial advancements have been made in the understanding and application of biomass-based carbon capture and storage, with improved methods for carbon sequestration and biomass conversion processes. As a result, more researchers are engaging with BECCS as a viable solution for achieving net-negative emissions. In terms of contributing countries, the United Kingdom has had the highest number of affiliations, signaling its leadership in BECCS research, followed by prominent contributors such as the United States, China, India, and Germany. These countries have developed robust research programs and policy frameworks that support the integration of BECCS into national climate strategies. The most recent publications on this subject have emerged from countries like Canada, Malaysia, and Australia, suggesting a global spread of interest in BECCS across diverse regions. In contrast, the earliest studies on BECCS were published by researchers in Switzerland, indicating that the foundation of BECCS research can be traced back to early efforts in Europe. This global participation underscores the growing international recognition of BECCS as a critical technology for sustainable development and climate change mitigation.

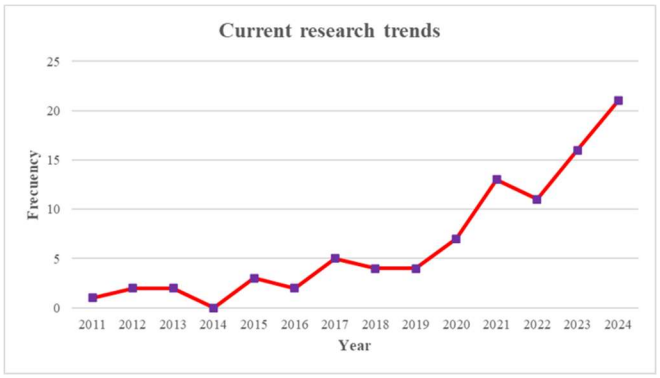


Fig. 1 Production of scientific articles related to biomass-based carbon capture and storage

C. VOS mapping of Title, Abstract, and Author Keywords

According to the keywords organized by the author in Fig. 2(a) and (b), the map serves as a visual representation of the interconnections among keywords pertinent to different dimensions of environmental sustainability and climate change. The size of the nodes corresponds to the frequency of the keywords in the analyzed literature, and the thickness of the edges indicates the strength of the connections between them. The dimensions of the nodes reflect the prevalence of these keywords within the reviewed literature, while the thickness of the connecting edges signifies the intensity of their relationships. This particular cluster is primarily characterized by keywords such as "climate change," "carbon capture," "carbon dioxide," and "carbon footprint," underscoring the pivotal importance of carbon management in the fight against climate change. Additionally, it encompasses terms like "sustainability," "environmental impact," "life cycle assessment," and "circular economy," which collectively highlight the broader framework of sustainability and the imperative to evaluate the environmental consequences of various practices. Furthermore, keywords such as "hydrogen" and "direct air capture" are notably featured in this cluster, reflecting an increasing focus on technological innovations aimed at mitigating climate change. The color scheme utilized in the map indicates a temporal progression in research focus. Keywords that are older are depicted in blue, whereas more recent keywords are shown in green. This

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differentiation highlights a shift in research priorities over time, with an increasing focus on emerging technologies and innovative methodologies. It is crucial to recognize that VOSviewer maps serve as a visual tool for illustrating keyword co-occurrence, but they do not inherently demonstrate causal relationships or the extent of research within each domain. To achieve a comprehensive understanding of the research landscape, it is vital to supplement bibliometric analysis with an in-depth examination of individual studies.

Based on the data presented, a gap analysis emerges from several aspects of research on biomass- based carbon capture and storage. First, the map primarily emphasizes the environmental and technological dimensions of climate change mitigation, while placing comparatively less focus on social and economic considerations. Future investigations could delve into the social ramifications of climate change mitigation strategies, particularly concerning equity, justice, and public acceptance. Furthermore, conducting economic evaluations of various mitigation approaches could yield significant insights for policymakers. The map does not clearly delineate the influence of policy and governance in facilitating climate action. Additional research could assess the efficacy of diverse policy instruments, including carbon pricing, subsidies, and regulations, in fostering sustainable practices. Moreover, the significance of international collaboration and global governance in tackling climate change merits further exploration. Although the map recognizes the critical role of technological innovation, a more thorough examination of the potential effects of emerging technologies—such as carbon capture and storage, renewable energy sources, and green hydrogen— is essential. Research efforts could concentrate on evaluating the environmental, social, and economic consequences of these technologies, as well as identifying obstacles to their broader implementation.

TABLE III. LIST TOPIC GENERATED BY AUTHOR'S KEYWORDS

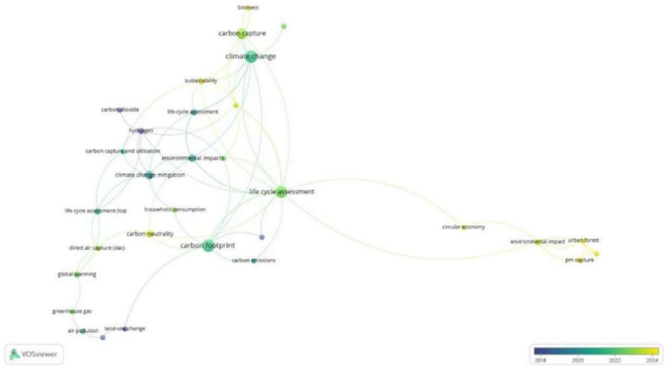
Topic label	Author keywords
Topic 1 Strategies for mitigating climate change	Air Pollution, carbon neutrality, direct air capture, global warming, greenhouse gas, integrated assessment, land-use change, life cycle assessment (LCA)
Topic 2 Environmental Impact Assessment	Carbon capture, climate change mitigation, environmental impacts, household consumption, sustainability, life cycle assessment (LCA)
Topic 3 Nature-Based Solutions for Urban Sustainability	Circular economy, tree ecosystem services, urban forest
Topic 4 Technological Innovation and Sustainability	Carbon dioxide, hydrogen, planetary boundaries, techno-economic analysis
Topic 5 Sustainable Development	Carbon capture, carbon emissions, carbon footprints, life cycle assessment (LCA)
Topic 6 Biomass-Based Carbon Capture and Storage (BECCS)	Biomass, carbon capture, climate change, decarbonization

The map emphasizes the significance of climate change mitigation, yet it is crucial to recognize the importance of climate change adaptation, especially in areas that are particularly susceptible. Future investigations should consider approaches to enhance resilience against the effects of climate change, including severe weather phenomena, rising sea levels, and water shortages. The map

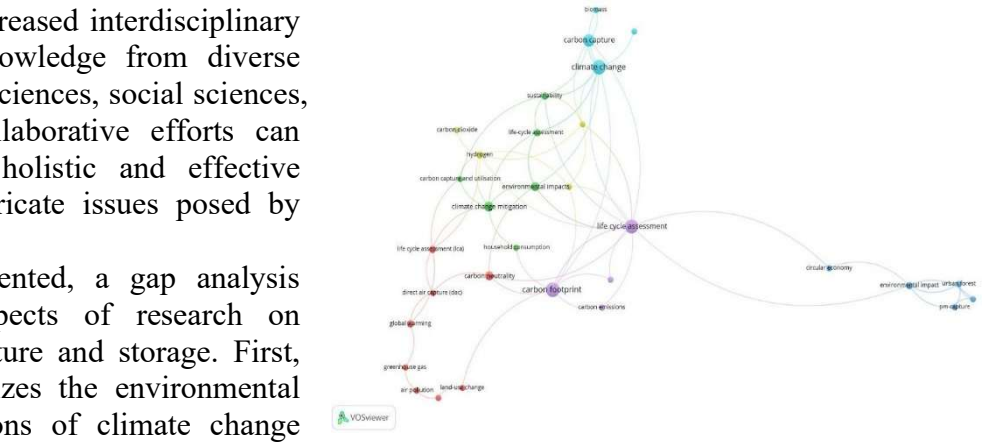
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indicates a necessity for increased interdisciplinary research that combines knowledge from diverse domains, including natural sciences, social sciences, and engineering. Such collaborative efforts can facilitate the creation of holistic and effective strategies to tackle the intricate issues posed by climate change.

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(a)



(b)

Fig. 2 Co-occurrence author keywords: clusters (a) and year of publication (b)

Moreover, the significance of international collaboration and global governance in tackling climate change merits further exploration. Although the map recognizes the critical role of technological innovation, a more thorough examination of the potential effects of emerging technologies—such as carbon capture and storage, renewable energy sources, and green hydrogen— is essential. Research efforts could concentrate on evaluating the environmental, social, and economic consequences of these technologies, as well as identifying obstacles to their broader implementation.

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IV. CONCLUSIONS

This bibliometric review underscores the increasing importance of biomass-based carbon

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capture and storage (BECCS) as a pivotal technology in the global initiative to mitigate climate change and foster sustainable development. An examination of research trends spanning from 2011 to 2024 indicates a significant rise in scientific publications, especially from 2020 onwards, which signifies a growing interest and acknowledgment of BECCS as a feasible approach to achieving negative carbon emissions. This increase is propelled by the pressing need to tackle climate change and the potential of BECCS to significantly contribute to the decarbonization of energy systems and facilitate the transition to a low-carbon economy. From a technological perspective, BECCS has experienced considerable progress, with research concentrating on enhancing the efficiency and scalability of carbon capture methods, alongside the optimization of biomass conversion processes. Nevertheless, considerable challenges persist regarding economic viability, technical intricacies, and societal acceptance. Overcoming these obstacles will necessitate ongoing innovation, strong policy backing, and international cooperation to establish conducive conditions for the extensive implementation of BECCS technologies.

The United Kingdom, the United States, and China have established themselves as frontrunners in the research of Bioenergy with Carbon Capture and Storage (BECCS), while emerging nations such as Canada, Malaysia, and Australia are also making significant contributions, reflecting an increasing global interest in this area. Although the potential of BECCS is widely recognized, its effectiveness in achieving sustainable development goals (SDGs) hinges on addressing several critical challenges, including high operational expenses, conflicts over land use, and the environmental risks associated with carbon dioxide storage. This review emphasizes the necessity of interdisciplinary research that integrates technological advancements, policy development, and social factors. Future investigations should prioritize enhancing the economic feasibility of BECCS, facilitating its integration with current energy infrastructures, and tackling public apprehensions regarding environmental and land-use issues. Additionally, the ongoing establishment of supportive regulatory measures and financial incentives will be crucial for the widespread adoption of BECCS technologies and their meaningful contribution to global climate objectives.

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