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Article

Biochar Application for Soil Carbon Sequestration and Greenhouse Gas Mitigation in Forest Ecosystems: A Bibliometric Analysis Using CiteSpace

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Abstract

Research on biochar application in forest soil carbon sequestration and greenhouse gas (GHG) mitigation has evolved into a rapidly expanding and increasingly sophisticated field. To address the lack of systematic evaluation, this study employed a bibliometric approach using the Web of Science database to analyze literature published between 1996 and 2025. The visualization and analysis were conducted using CiteSpace, a bibliometric tool that identifies emerging trends and research frontiers through co-citation networks, keyword mapping, and burst detection. Our analysis reveals a sustained rise in publication output, with China, the United States, and the European Union identified as leading contributors, whose influence continues to grow. Thematic mapping indicates a clear progression from early studies focused on "black carbon" and "soil organic matter" toward mechanism-driven investigations, with the "microbial community" now recognized as a key mediator of biochar's ecological effects. Keyword clustering and burst analysis further reveal that biochar's influence on soil fertility and microbial functioning has become central to its role in enhancing soil carbon sequestration and mitigating GHG emissions. While biochar's capacity to enhance SOC stocks is widely affirmed, its variable impact on GHG fluxes highlights the need for integrated assessments of net Global Warming Potential (GWP). Despite promising advances, critical barriers persist, including the paucity of long-term, landscape-scale field trials and the absence of standardized production protocols, both contributing to inconsistent outcomes across studies. Future research should prioritize mechanistic studies across diverse forest ecosystems and adopt comprehensive life cycle assessments that account for both soil and vegetation-mediated carbon sinks.

Keywords: bibliometrics; climate change mitigation; forest soil; knowledge mapping; research trend; sustainable forest management

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1. Introduction

Forest ecosystems play a pivotal role in the global carbon cycle, serving as a crucial buffer against climate change by absorbing a significant fraction of anthropogenic CO_2

emissions [1,2]. Collectively, the world's forests act as a vast and persistent carbon sink, sequestering an estimated 3.5 Pg C yr^{-1} to nearly half of global fossil fuel emissions [3]. However, the durability and future efficacy of this carbon sink are increasingly uncertain. Ongoing deforestation, escalating natural disturbances, and the complex physiological responses of mature forests to a changing climate threaten to erode this critical function [4,5]. These vulnerabilities highlight the urgent need for robust land management strategies aimed at safeguarding and enhancing the carbon sequestration potential of forest ecosystems [6–8].

In addition to absorbing atmospheric CO_2 through photosynthesis, forest ecosystems exert considerable control over the exchange of non-CO_2 greenhouse gases, notably methane (CH_4) and nitrous oxide (N_2O), which possess global warming potentials far exceeding that of CO_2 [6]. Forest soils, often containing carbon stocks equal to or greater than those in aboveground biomass [9,10], function not only as long-term carbon reservoirs but also as active biogeochemical interfaces regulating CH_4 and N_2O fluxes [11–13]. While soil organic carbon enhances CH_4 sink strength [14], it concurrently influences N_2O production through microbially driven pathways [15,16]. Emission rates and mechanisms vary regionally in response to climatic gradients and land management interventions, yet their impact remains inadequately characterized [2,11]. Addressing this gap is essential to unlocking the full mitigation potential of forest ecosystems, which depends on integrated strategies that strengthen carbon sequestration while minimizing non-CO_2 emissions.

Scientific interest in biochar as a soil amendment began with studies of Amazonian Dark Earths, exceptionally fertile soils in the Amazon Basin enriched by pre-Columbian practices of adding charred biomass [17]. This historical linkage to forest ecosystems highlights that the conceptual origins of biochar research are inherently forest-based. Pioneering publications by Lehmann et al. in the early 2000s systematically characterized these soils and advanced biochar as a promising strategy for enhancing soil quality and achieving long-term carbon sequestration [18,19]. Their work formally distinguished biochar from conventional charcoal, defining it as a material intentionally produced for soil application. This foundational research ignited a global surge of inquiry into biochar's multifunctional potential to deliver renewable energy, mitigate climate change, and improve soil health [20].

Biochar is increasingly recognized as a climate-smart intervention in forest ecosystems [21–24]. Its primary climate benefit is attributed to long-term carbon sequestration [25]. First, biochar is a chemically recalcitrant form of carbon with a low turnover rate, allowing it to persist in soils for decades to millennia [26]. Second, biochar can suppress the decomposition of native soil organic carbon, a phenomenon known as negative priming, thereby preserving existing carbon stocks [27]. Third, by improving soil physical structure and nutrient availability, biochar enhances plant productivity and supports forest regeneration, which contributes to additional carbon accumulation in biomass and soils [28,29]. However, its net effect on the soil carbon cycle is not always straightforward. The influence of biochar on soil CO_2 fluxes, for instance, has been shown to vary considerably, with different field studies reporting increasing [30,31] or negligible effects [32,33].

The impact of biochar on N_2O and CH_4 fluxes is also highly context-dependent, varying significantly with climate, soil type, and agricultural practices. Several incubation studies and field trials in subtropical plantations demonstrate that biochar can markedly suppress N_2O emissions largely via improved aeration, higher soil pH, and constrained nitrification/denitrification processes [34–36]. In contrast, long-term or multi-site field experiments carried out in N-limited temperate and boreal forests consistently report no detectable change in N_2O fluxes following biochar addition [32,33,37]. Extended monitoring at single sites and across regions generally find that biochar neither enhances nor diminishes the net CH_4 sink strength of upland forest soils [32,33]. However, when biochar is co-applied with large amounts of mineral nitrogen, CH_4 emissions can increase significantly, presumably because elevated NH_4^+ concentrations inhibit high-affinity methanotroph [31].

Bibliometric analysis provides a robust quantitative framework for systematically characterizing the intellectual structure of a research domain by statistically analyzing publication data to uncover influential contributors, collaboration networks, and thematic trajectories [38,39]. While this approach has been widely applied to explore the evolution of biochar research in agriculture ecosystems [40–42], its application to forest ecosystems, particularly concerning soil carbon sequestration and GHG mitigation, remains limited. A recent study by Chen et al. [43] offered a broad overview of biochar-related studies in forest soils, identifying GHG emissions as an emerging hotspot. However, as the literature on biochar's role in climate-focused forest soil processes continues to expand rapidly, a dedicated bibliometric synthesis is urgently needed to consolidate existing findings and inform future investigation.

Bibliometrics is a quantitative research method that utilizes mathematical and statistical techniques to analyze the characteristics of academic literature, thereby enabling assessment of disciplinary dynamics and forecasting future research trajectories [38,39]. With the growing adoption of bibliometric methods, a wide range of visualization software has been developed. Among them, CiteSpace, created by Chen et al. [44], has become one of the most widely used tools in bibliometric studies. CiteSpace-based analyses have been increasingly applied in environmental and ecological research domains [45,46]. In this study, we sought to identify key research themes concerning biochar application for forest soil carbon sequestration and GHG mitigation. CiteSpace (version 6.3) was employed to visualize keyword co-occurrence patterns, publication distribution by countries/regions and institutions, and overall publication volume.

Accordingly, this study employs CiteSpace software (version 6.3) to conduct a visual bibliometric analysis of publications retrieved from the Web of Science Core Collection (1996–2025). By mapping the conceptual and collaborative landscape underpinning biochar application for soil carbon sequestration and GHG mitigation in forest ecosystems, the analysis aims to (1) identify key research gaps and evolving trends in the field; (2) visualize the interconnections among major subtopics; (3) outline a promising trajectory for future research.

2. Materials and Methods

2.1. Data Collection

Based on the aim of this study, we initially identified journal articles assessing the effects of biochar application on soil carbon sequestration of forest soil from 1996 to 2025 through Web of Science Core Collection (WOSCC) database. The search strategy employed the following terms: [TS = ("charcoal" OR "Biochar") AND TS = ("Soil organic carbon" OR "soil carbon" OR "soil sequestration") AND TS = ("Forest")], collecting a total of 295 relevant publications.

Subsequently, we retrieved journal articles published between 1997 and 2025 that investigate the impact of biochar application on GHG emissions from forest soils, with a focus on CH_4, N_2O, and CO_2. The search was conducted using the WOSCC database with the following terms: [TS = ("charcoal" OR "biochar") AND TS = ("soil" AND "forest") AND TS = ("N_2O" OR "CH_4" OR "CO_2" OR "soil respiration")], resulting in a total of 256 publications.

To ensure the integrity and relevance of the bibliometric dataset, a three-step screening protocol was implemented. A total of 551 publications were initially retrieved. First, duplicate entries (n = 67 publications) were identified and removed through meticulous cross-verification of titles, abstracts, and author information, resulting in a refined dataset of 484 publications. Second, a language filter was applied, retaining only English-language records and excluding non-English publications. Third, publication type filtering was conducted to preserve only those records classified as original research articles, review papers, proceedings papers, early access items, and data papers, formats widely recognized as scholarly contributions. Other document types, such as book chapters and retracted articles, were excluded from the final analysis.

2.2. Statistical Analysis

In this study, we employed CiteSpace software (version 6.3) to conduct a visual bibliometric analysis. First, we generated a keyword co-occurrence map to identify the core topics and intellectual structure of the research domain. Subsequently, we performed keyword clustering using the Log-likelihood Ratio (LLR) algorithm to group related terms into thematic clusters, thereby revealing the major research sub-fields. To investigate the evolution of these topics, we constructed a timeline view to illustrate the chronological emergence and development of these clusters. Finally, we applied burst detection analysis to identify keywords that experienced a sudden increase in usage, which allowed us to pinpoint emerging research hotspots and scholarly trends. The burst detection analysis is based on Kleinberg's algorithm, which identifies keywords with a sharp increase in frequency over time. Burst strength is a calculated metric that quantifies the intensity of this surge. A higher strength value indicates a more significant and rapid increase in scholarly attention on that topic during a specific period, signifying an important emerging trend or research frontier in the field.

3. Results

3.1. Biochar Application on Soil Carbon Sequestration of Forest Ecosystem

3.1.1. Research Hotspot and Trend

The co-occurrence map of keywords highlighted multiple focal points of scholarly interest (Figure 1). The most frequently occurring keywords include "soil organic carbon", "carbon sequestration", "biochar", "black carbon", and "forest" indicating a strong focus on the role of biochar in enhancing soil carbon storage within forest ecosystems. Clusters such as "nitrogen", "microbial biomass", and "organic matter" suggest increasing attention to the interactions between biochar, nutrient cycling, and microbial dynamics. Additionally, terms like "greenhouse gas emissions", "decomposition", and "mineralization" reflect a growing interest in the broader ecological impacts of biochar, particularly in mitigating climate change.

We conducted a keyword cluster analysis using the Log-likelihood Ratio method and identified ten thematic clusters (Figure 2). One major cluster center on "black carbon" reflecting foundational studies on the stability and long-term carbon retention properties of biochar. Other prominent clusters focus on "soil organic carbon" and "soil organic matter" emphasizing biochar's role in enhancing soil carbon pools and improving soil fertility. Themes related to "negative priming effects", "microorganisms", and "deposition" highlight growing interest in microbial dynamics and biogeochemical interactions influenced by biochar amendments. The presence of clusters such as "carbon neutrality" and "fire sites" suggests a broader ecological and climate-related context, linking biochar research to carbon offset strategies and post-fire soil recovery. Additionally, the inclusion of "C-13 natural abundance" indicates the use of isotopic techniques to trace carbon cycling processes.

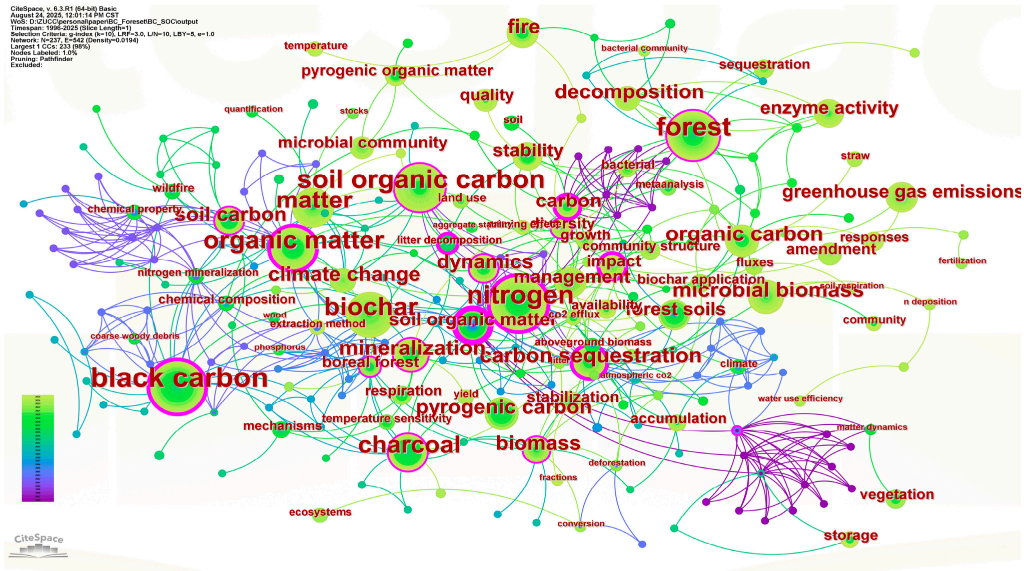

Figure 1. Keyword co-occurrence network of biochar application in forest soil carbon sequestration research (1996–2025).

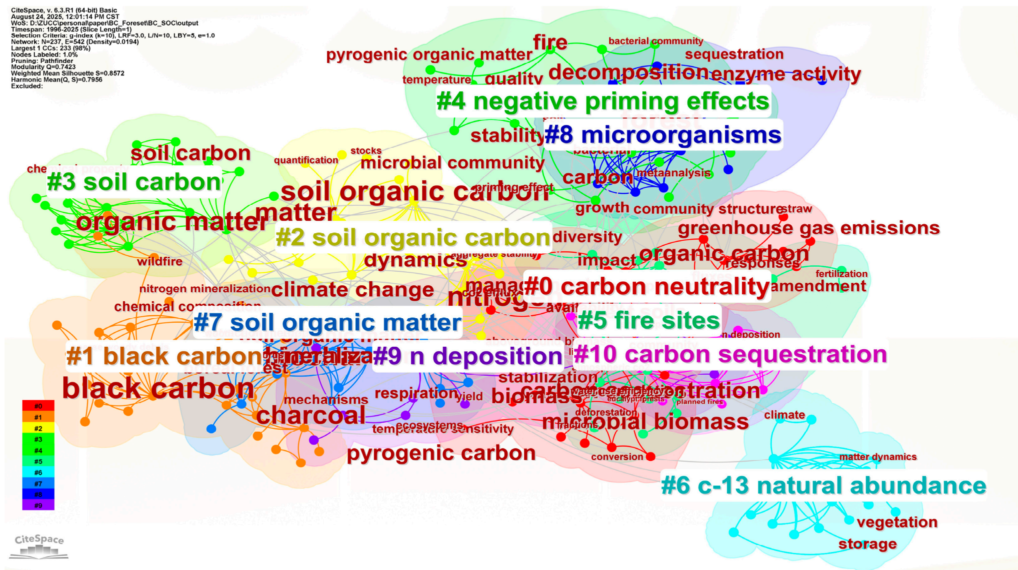

Figure 2. Keyword clustering map of biochar application in forest soil carbon sequestration research (1996–2025).

3.1.2. Timeline About Biochar Application on Forest Soil Carbon Sequestration

Figure 3 illustrates the timeline map of keyword clusters concerning biochar application in forest soil carbon sequestration, revealing the temporal evolution of research themes from 1996 to 2023. Early studies (1996–2005) were primarily centered on fundamental concepts such as "black carbon", "organic matter", and "soil organic carbon", reflecting initial efforts to understand biochar's basic properties and its interaction with forest soils. Between 2006 and 2015, the focus expanded to include mechanistic processes, with increased attention to keywords like "microbial biomass", "mineralization", and "carbon sequestration". From 2016 onward, there was a notable rise in keywords related to climate relevance, such as "carbon neutrality", "greenhouse gas emissions", and "climate change mitigation" indicating a strategic shift toward policy-oriented and global impact research.

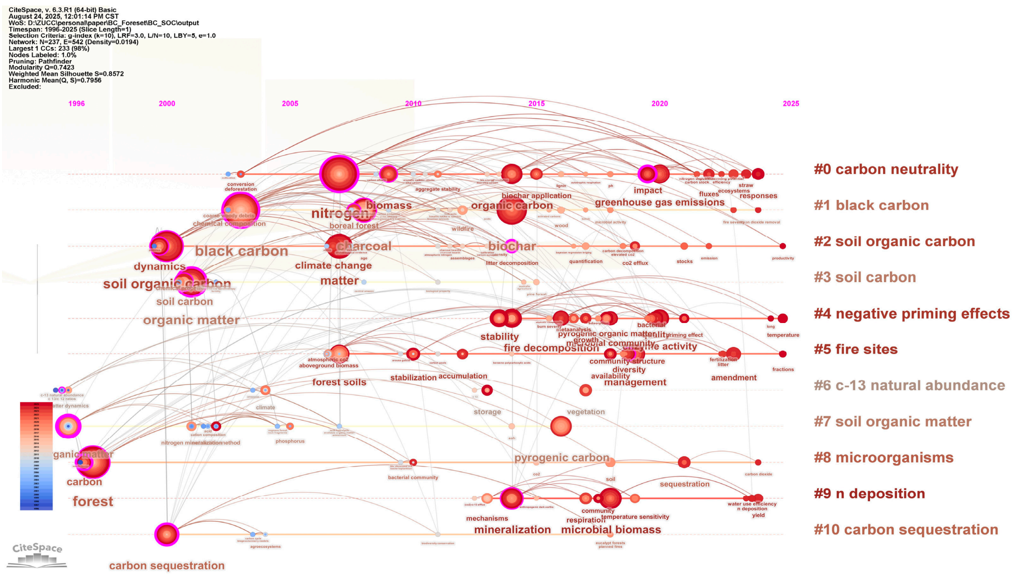

Figure 3. Timeline visualization of keyword clusters in biochar application for forest soil carbon sequestration research (1996–2025).

Figure 4 displays the burst keywords map, highlighting the top 15 keywords with the strongest citation bursts in research on forest soil carbon sequestration under biochar application from 1996 to 2025. The earliest burst occurred for "soil organic matter" beginning in 1996 and lasting until 2010, indicating foundational interest in soil composition. Keywords such as "atmospheric CO_2" and "carbon sequestration" showed strong bursts between 1998 and 2012, reflecting growing attention to climate-related functions of biochar. From 2010 onward, emerging keywords like "wildfire", "pyrogenic carbon", and "temperature sensitivity" gained prominence, suggesting a shift toward understanding biochar's role in dynamic forest processes and carbon stability. Notably, recent bursts include "bacterial" (2021–2025), "management" (2023–2025), and "amendment" (2023–2025), pointing to a current emphasis on microbial interactions and practical implementation strategies.

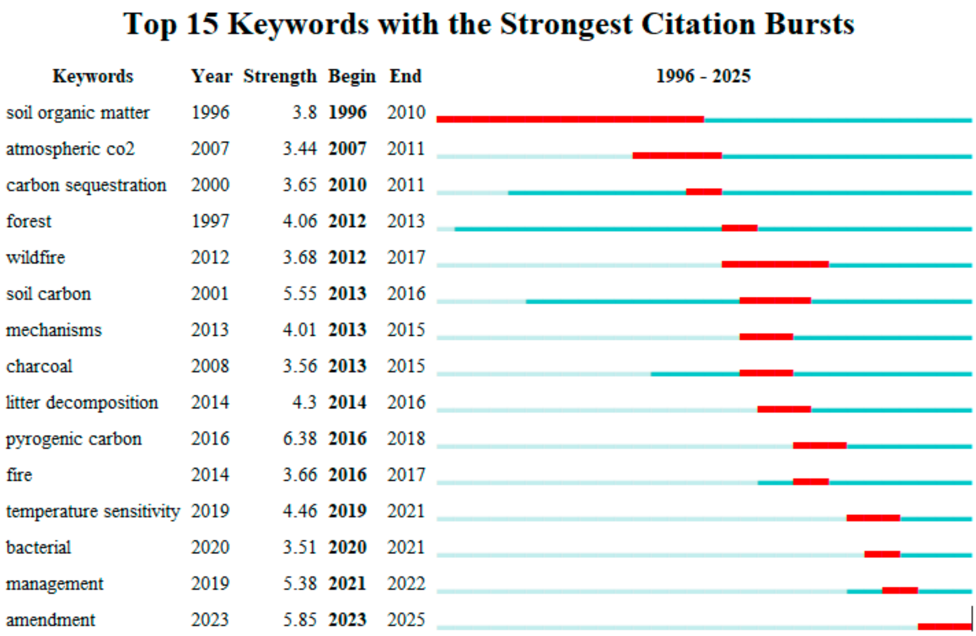

Figure 4. Burst keyword analysis of forest soil carbon sequestration research under biochar application (1996–2025).

3.1.3. Countries and Global Publication Count

Figure 5 illustrates the global annual publication volume and citation trends related to biochar application on forest soil carbon sequestration from 1996 to 2025. The number of publications remained low and relatively stable before 2008, followed by a gradual increase between 2009 and 2016. A notable surge occurred after 2017, with publication output peaking in 2023 at over 40 articles. Citations also showed a sharp upward trajectory, particularly from 2018 onward, reaching a maximum of over 1300 citations in 2023. Although both publications and citations slightly declined in 2024, the overall trend reflects growing global interest and academic recognition of biochar's role in forest soil carbon dynamics.

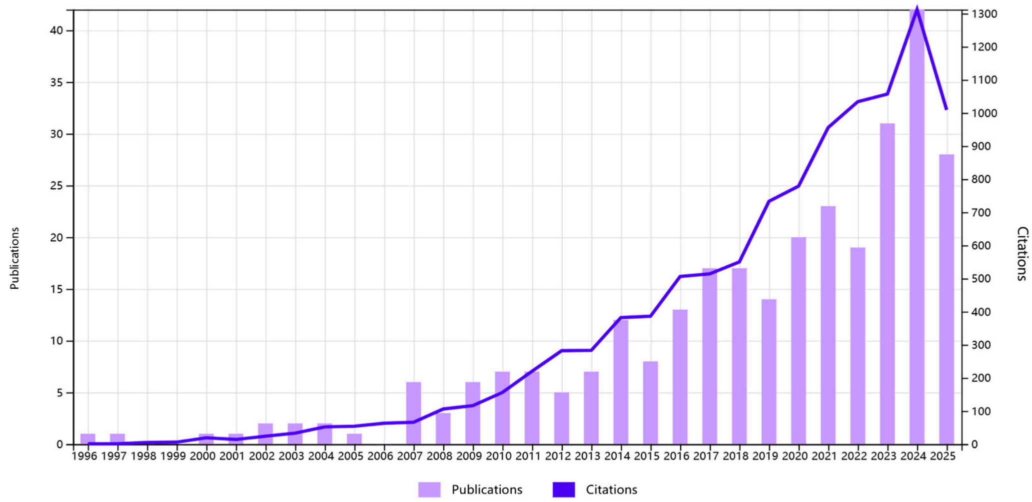

Figure 5. Global annual publication trends on biochar application for forest soil carbon sequestration (1996–2025).

Figure 6 presents the national publication volume on biochar application in forest soil carbon sequestration. China and the United States are the leading contributors, with China showing the highest number of publications, followed closely by the USA. Other active countries include Australia, Germany, Canada, and Japan, each demonstrating substantial research output. European nations such as the United Kingdom, France, Spain, and Italy also show moderate levels of publication activity, while emerging contributions are observed from countries like Brazil, Ethiopia, and Kenya.

Figure 7 presents the institutional collaboration network in the field of biochar application for forest soil carbon sequestration. The Chinese Academy of Sciences and Zhejiang A&F University are the most productive institutions, with 25 and 24 publications, respectively. Other institutions with more than 10 publications include the United States Department of Agriculture (USDA), the Commonwealth Scientific and Industrial Research Organization (CSIRO), Griffith University, and the United States Forest Service. These organizations demonstrate sustained research activity and frequent collaboration across national boundaries. Additional contributors with fewer than 10 publications include Consejo Superior de Investigaciones Científicas (CSIC), Cornell University, Oregon State University, and the State Key Laboratory of Soil and Sustainable Agriculture.

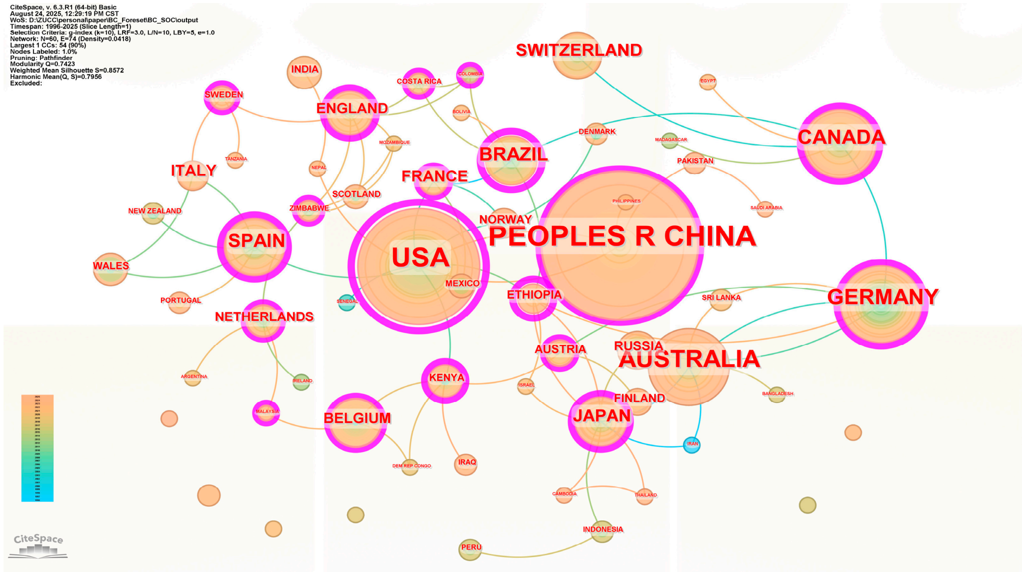

Figure 6. National publication output on biochar application for forest soil carbon sequestration research (1996–2025).

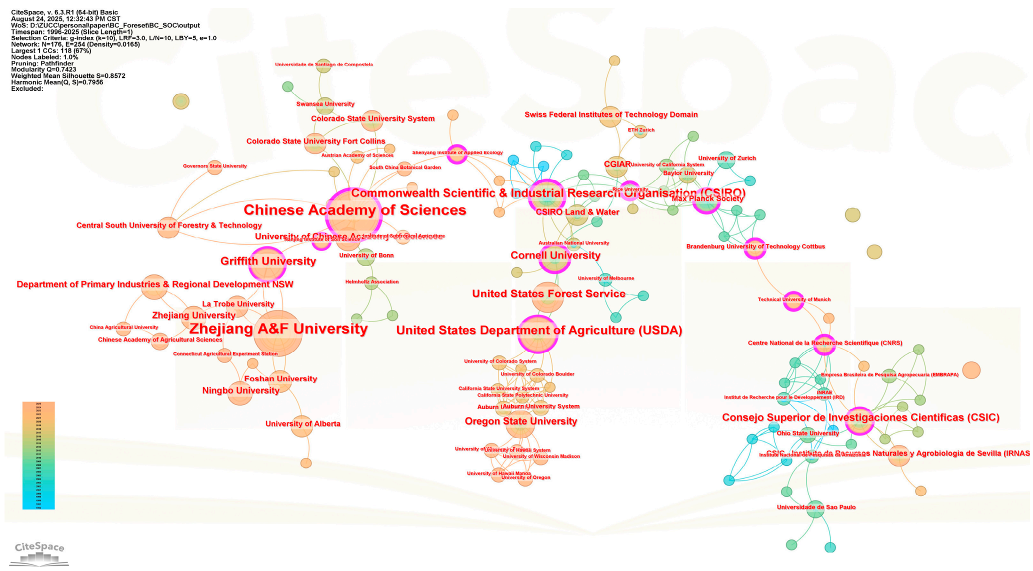

Figure 7. Institutional collaboration network in biochar application for forest soil carbon sequestration research (1996–2025).

3.2. Biochar Application on Greenhouse Gas Emission of Forest Ecosystem

3.2.1. Research Hotspot and Trend

Figure 8 displays the keywords co-occurrence map related to forest GHG emissions under biochar application. High-frequency keywords such as "biochar", "forest", "greenhouse gas emissions", "carbon sequestration", "black carbon", and "nitrogen" dominate the network, indicating the primary focus areas. Closely linked keywords like "microbial biomass", "soil respiration", "N_2O emissions", and "temperature sensitivity" reflect an emphasis on soil microbial processes and emission mechanisms. Additional terms including "charcoal", "organic carbon", and "climate change" suggest interdisciplinary connections across soil science, ecology, and climate mitigation.

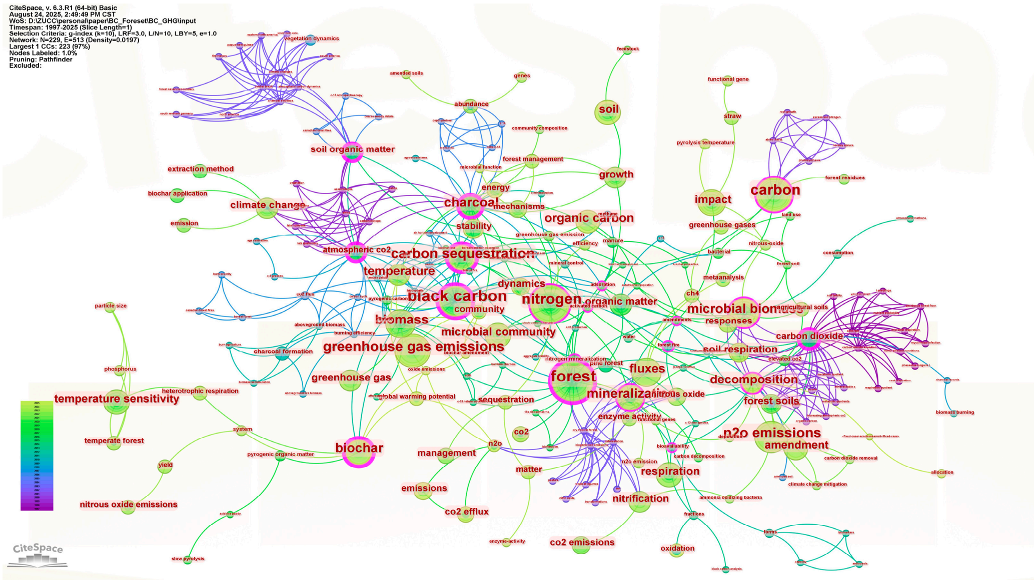

Figure 8. Keyword co-occurrence network of forest greenhouse gas emissions under biochar application (1997–2025).

The keyword cluster map identified several thematic groups related to forest greenhouse gas emissions under biochar application (Figure 9). Major research areas included "carbon sequestration", "forest management", "global warming potential", and "nitrous oxide", reflecting core scientific interests in carbon storage strategies, land use practices, and the mitigation of climate-relevant gases. Other clusters such as "pyrolysis temperature", "microbial biomass", and "soil organic matter" emphasized the influence of biochar production conditions and soil biological activity on emission dynamics. These themes suggest a strong focus on how biochar characteristics and microbial interactions shape greenhouse gas fluxes in forest soils. Keywords like "grass" and "forest soil" pointed to broader ecological contexts, including vegetation type and soil heterogeneity, which may affect biochar performance and long-term carbon stability.

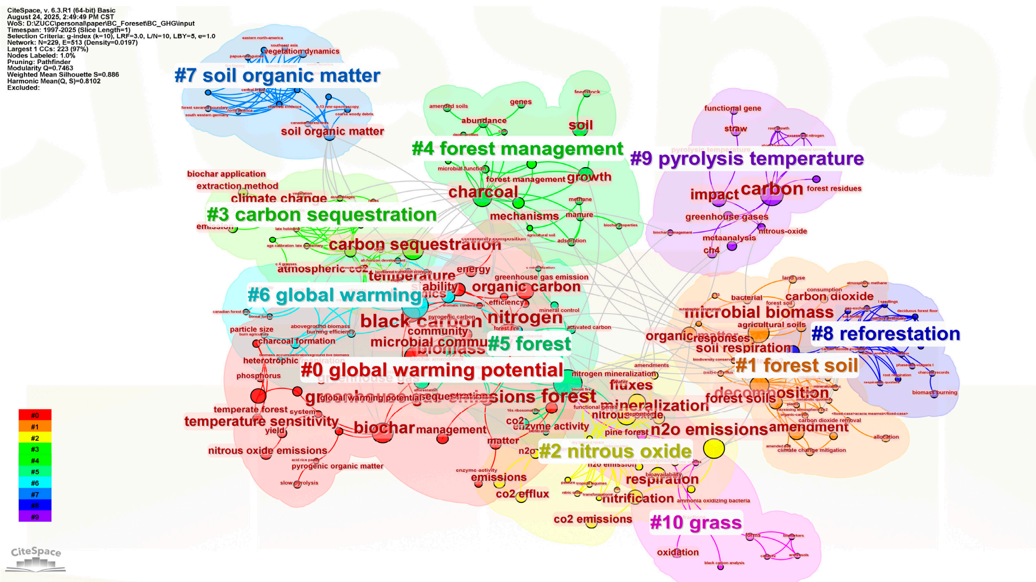

Figure 9. Keyword clustering map of forest greenhouse gas emissions under biochar application (1997–2025).

3.2.2. Timeline About Biochar Application on Forest Soil GHGs Mitigation

The timeline map illustrates the temporal evolution of keyword clusters in research on forest greenhouse gas emissions under biochar application (Figure 10). Early studies before 2010 focused on foundational concepts such as "carbon", "charcoal", and "soil organic matter", reflecting initial interest in biochar's basic properties and its interaction with forest soils. Between 2010 and 2015, research expanded to include "carbon sequestration", "microbial biomass" and "forest management", indicating a growing emphasis on soil processes and ecosystem-level applications. From 2016 onward, keywords like "greenhouse gas emissions", "nitrous oxide", and "global warming potential" became increasingly prominent, suggesting a shift toward climate-oriented research and mitigation strategies.

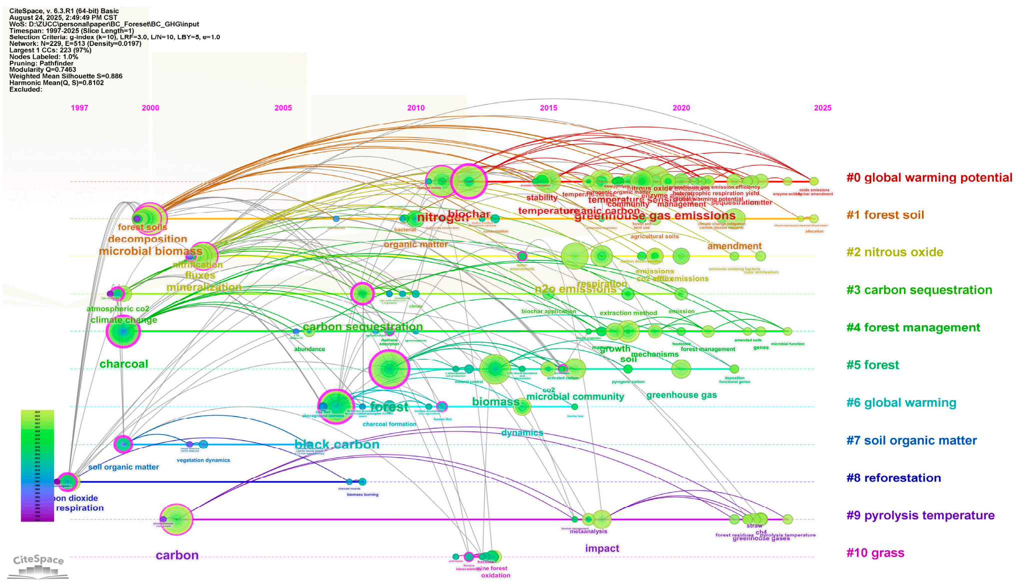

Figure 10. Timeline visualization of keyword clusters in forest greenhouse gas emissions under biochar application (1997–2025).

The burst keywords map highlighted the top fourteen keywords with the strongest citation bursts in research on forest soil greenhouse gas emissions under biochar application from 1997 to 2025 (Figure 11). Early bursts included "carbon dioxide", beginning in 1997 and lasting until 2016, and "soil organic matter" from 1999 to 2015, reflecting foundational interest in carbon dynamics and soil composition. Between 2001 and 2012, keywords such as "vegetation dynamics", "atmospheric CO_2" and "black carbon" showed notable bursts, indicating growing attention to ecosystem-level processes and biochar's role in atmospheric carbon regulation.

In more recent years, keywords like "temperature sensitivity", "CO_2 emissions" "management" and "nitrification" exhibited strong bursts from 2019 onward, suggesting a shift toward microbial mechanisms, emission control strategies, and practical land management applications. The emergence of "management" and "nitrification" after 2021 points to an increasing focus on applied solutions and nitrogen-related processes in forest soils. Overall, the burst analysis revealed a transition from broad carbon-related themes to more targeted studies on emission pathways and biochar's functional role in forest soil systems.

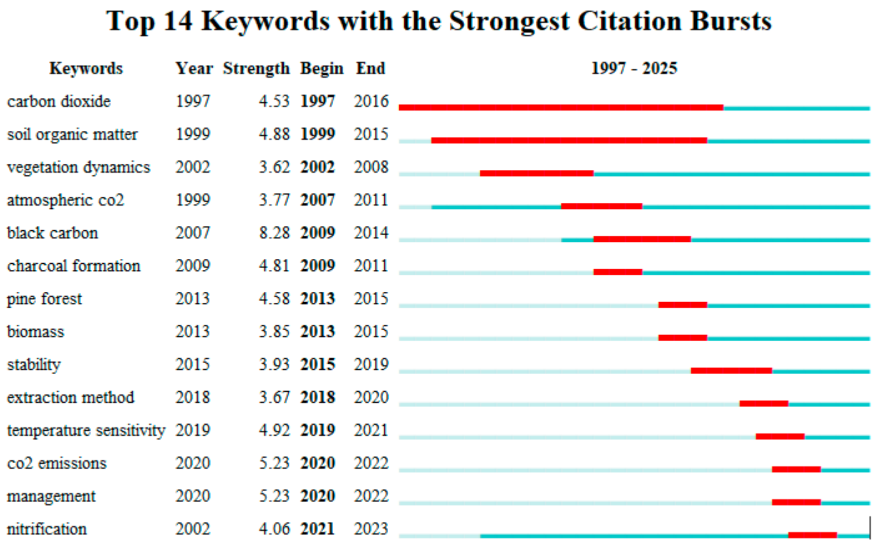

Figure 11. Burst keyword analysis of forest soil greenhouse gas emissions under biochar application (1997–2025).

3.2.3. Countries/Regions and Institution Analysis

The global annual publication volume on biochar application for forest soil greenhouse gas mitigation showed a clear upward trend from 1997 to 2025 (Figure 12). Before 2010, publication output remained low, with fewer than five articles per year. A steady increase began around 2011, followed by a sharp rise after 2017. The number of publications peaked in 2023 with over 28 articles, while citations reached their highest point the same year, exceeding 1400. Although both metrics slightly declined in 2024, the overall trajectory indicated growing academic interest and recognition of biochar's role in mitigating greenhouse gas emissions from forest soils. This trend reflects the expanding scope of research in this field, driven by increasing concern over climate change and the need for sustainable land management strategies.

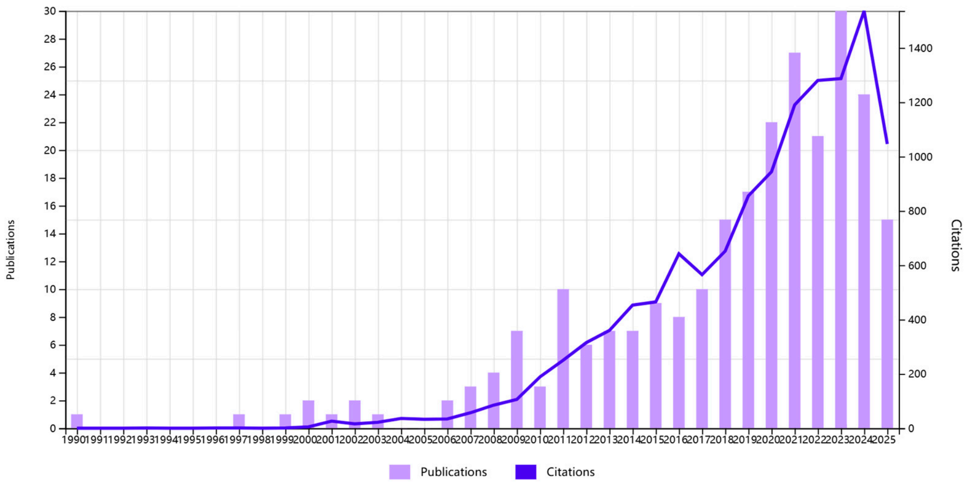

Figure 12. Global annual publication trends on biochar application for forest soil greenhouse gas mitigation (1997–2025).

The national publication map illustrates global research activity on biochar application for forest soil greenhouse gas mitigation (Figure 13). China and the United States were the most active contributors, with China showing the highest publication volume. Australia, Canada, and Germany also demonstrated strong research output, forming key nodes in the global collaboration network. Other countries with notable contributions included

Japan, Spain, England, France, and Brazil, while emerging participation was observed from nations such as Ethiopia, India, and Poland.

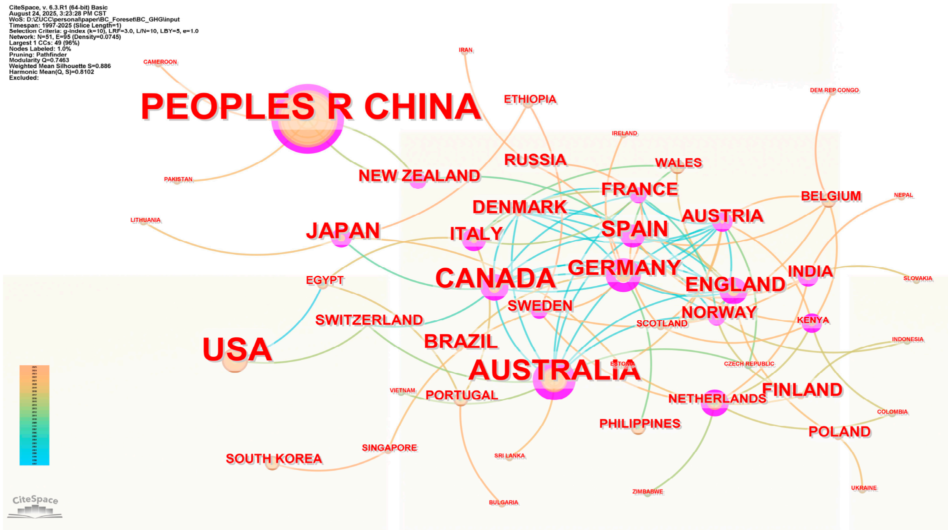

Figure 13. National publication output on biochar application for forest soil greenhouse gas mitigation (1997–2025).

The institutional collaboration network revealed active partnerships among global research organizations studying biochar application for forest soil greenhouse gas mitigation (Figure 14). Zhejiang A&F University and the Chinese Academy of Sciences were the most productive institutions, with 27 and 25 publications, respectively. Both have demonstrated sustained research output and extensive collaboration since 2018 and 2010, respectively, forming central hubs in the network. Their partnerships span a wide range of domestic institutions, including Zhejiang University, Ningbo University, and Nanjing Forestry University, as well as international collaborators such as the University of Alberta, Griffith University, and La Trobe University. Other institutions with notable contributions include Elizabeth Macarthur Agricultural Institute, Auburn University, and the United States Forest Service, each publishing between 7 and 10 articles. Additional participants such as Hokkaido University, University of Eastern Finland, and British Columbia University have engaged in collaborative efforts, though with fewer publications.

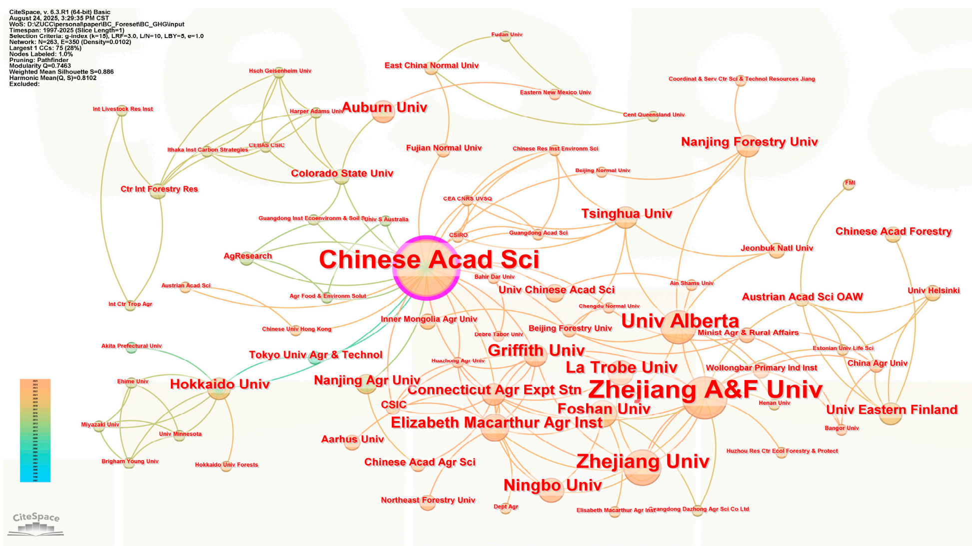

Figure 14. Institutional collaboration network in biochar application for forest soil greenhouse gas mitigation research (1997–2025).

4. Discussion

4.1. Future Research Hotspots and Emerging Trends

Our analysis of the keyword co-occurrence and thematic evolution maps concerning biochar's effects on SOC and GHG mitigation in forest ecosystems reveals a developmental trajectory centered on its origin, attributes, and ecological functions. For soil carbon sequestration, early themes such as black carbon reflect interest in biochar formation through wildfire and pyrolysis, with temperature as a key determinant of its stability and sorption capacity [47]. Biochar is a carbon-rich production by heating biomass with limited oxygen atmosphere [48,49]. Biochar produced from different feedstock and at different temperatures can vary in their impact on soil properties and their environmental benefits. Although biochar is often expected to improve soil quality, recent findings from temperate forest ecosystems indicate that its effects on tree growth and productivity may be limited or inconsistent [50]. Therefore, more research is needed about the effects of different types of biochar on forest soils and forest types, in order to more effectively promote the sustainable use of biochar in forest soils.

As research advanced, central themes like soil organic carbon and microbial community emerged, highlighting biochar's role in modulating soil biota and enhancing soil carbon sequestration. Stable isotope techniques (e.g., C-13 tracing) have confirmed biochar's long-term persistence in soils and its contribution to SOC stabilization [51], while its adsorption properties affect microbial interactions [52]. According to the results we can conclude that soil microorganism and enzyme activity were the main reasons affecting forest soil potential of carbon sequestration and GHGs mitigation. Many studies have proved this [53,54]. The addition of biochar changed soil structure and soil properties, which provided new habitats and nutrients for microorganism and thus the soil respiration increased, leading to more CO_2 emission [55–57]. Recent frontiers have advanced from simple assessments of biochar's effect on total organic carbon content to the mechanistic understanding of its control over carbon pool stability and microbial processes [52,58,59]. Additionally, Li et al. [56] has revealed that biochar effectively reduces soil heterotrophic respiration by increasing the recalcitrancy of soil organic carbon and decreasing the activity of carbon-degrading microbes, thereby promoting stable carbon sequestration. This mechanistic finding moves beyond earlier phenomenological observations.

In addition, enzyme activity was an important indicator for microbial growth and activity, which can regulate global soil biogeochemical cycles [60]. However, biochar application did not significantly increase enzyme activity in a short time, and the reason for the result may relate to the feedstock of producing biochar and the type of enzyme [61]. A meta-analysis showed that the effects of biochar on microbial and enzyme activities varied in different soils [62]. This was because the optional living conditions for soil enzymes were different, and biochar application may not have a positive effect on all enzymes [63]. Moreover, soil aggregates were influenced by microbes community and SOC can be protected by soil aggregates to be decomposed [64]. With the increasing temperature, the stability and fixable of SOC were decreasing because SOC mineralization was depending on temperature [65]. Biochar cannot be decomposed easily by microbes but it changed microbial community, and microorganisms will accelerate the decomposition of the original SOC in the soil in the case of temperature rising [66].

In later thematic cycles, keywords such as carbon neutrality, greenhouse gas emissions and climate change mitigation reflect a shift from foundational soil science toward broader environmental and policy-oriented applications of biochar. This evolution in focus underscored biochar's potential not only as a soil amendment but also as a strategic tool for climate action and sustainable forest management. One such interaction is the triggering of complex microbial responses, notably the "priming effect", a phenomenon where external organic matter causes a rapid turnover of native soil organic matter [67]. This occurs because biochar's high porosity and large surface area change microbial habitats and enhance microbial and enzyme activity, which can lead to a short-term increase in greenhouse gas emissions and dynamic changes in soil organic carbon [56,57]. Understanding the interaction between biochar and microbial communities is crucial, as it elucidates the mechanisms by which biochar application acts as an effective forest management strategy for plantations. As reviewed by Li et al. [56], this practice can improve soil fertility, promote forest growth, increase biodiversity, and ultimately help restore the ecosystem's carbon sink function.

For GHG mitigation, the keyword cluster map reveals a structured thematic landscape in biochar-related forest GHG research, with central clusters such as carbon sequestration, forest management, global warming potential and nitrous oxide indicating a strong focus on biochar's role in mitigating major GHGs. These clusters highlight the scientific emphasis on quantifying biochar's impact on emission reduction and soil carbon dynamics [68–70]. Other thematic groups such as "pyrolysis temperature", "microbial biomass", and "soil organic matter" emphasized the influence of biochar production parameters and soil biological processes on emission behavior. These keywords suggest that microbial interactions and biochar characteristics play a critical role in shaping greenhouse gas fluxes in forest soils. Biochar enhances soil structure and water retention, promoting root development and aboveground biomass accumulation, which indirectly contributes to carbon sequestration [33,71].

Building on these thematic foundations, recent research has advanced biochar application from conceptual understanding to targeted mitigation strategies. Led by scholars including Zhou et al. [72], Cheng et al. [69], and Li et al. [73], their research has pioneered the development of biochar-based compound fertilizers that decrease the global warming potential of soil CH_4 and N_2O. Collaborating with international scholars such as Yakov Kuzyakov (University of Göttingen), their work provides key mechanistic insights, demonstrating that these novel fertilizers can increase methane uptake while high application rates reduce N_2O emissions by regulating labile nitrogen and microbial activity [35,72]. This body of research elevates biochar from a simple amendment to a sophisticated strategy for precise GHG mitigation.

In addition, a growing body of systematic research is concurrently evaluating the effects of biochar on SOC dynamics and GHG emissions [69,71,74]. Integrated studies indicate that biochar improves soil carbon storage and often leads to favorable changes in greenhouse gas emissions, although the effects can vary depending on conditions [75]. Across diverse forest ecosystems, including subtropical Moso bamboo plantations and temperate coniferous stands, biochar application reliably increases SOC stocks, thereby contributing to long-term carbon sequestration [69,73,74]. Its influence on GHG emissions, however, is more nuanced. Field studies consistently report substantial reductions in N_2O emissions and enhanced CH_4 uptake capacity, both of which contribute to lowering net radiative forcing [56,69]. In contrast, the impact on CO_2 fluxes remains variable: some investigations in Moso bamboo systems have observed elevated CO_2 emissions post-application, while studies in temperate forests and short-rotation plantations report negligible or transient effects [32,71]. Incubation experiments further suggest that biochar suppresses SOC mineralization relative to fresh organic inputs, a phenomenon attributed to its high chemical recalcitrance [52].

Taken together, the combination of durable carbon stabilization and mitigation of high-potency non-CO_2 gases frequently results in a net reduction in global warming potential (GWP), even under scenarios of increased CO_2 efflux [73]. Moso bamboo forests, which are fast-growing ecosystems with significant potential for climate change mitigation, provide a compelling example of this principle in action. Studies in these subtropical forests have demonstrated that biochar amendments can significantly increase carbon sequestration while simultaneously decreasing soil N_2O emissions [69], highlighting the great potential of this combined approach. These findings highlight the urgent need for more comprehensive, ecosystem-specific studies that jointly quantify SOC trajectories and multi-gas emissions [32,33]. Such integrative approaches are essential for accurately characterizing biochar's climate mitigation potential across varying forest types, application regimes, and management contexts.

4.2. Country and Institution

From the results of country/region analysis we can find that the number of research paper from China increased continually and cooperated with research universities and institutes. Until 2021, there were 23,100-billion-hectare forest areas in China and the forest cover rate was 24%. Although there was still a large gap comparing the average world level 30% [76], the Chinese government's policy of returning farmland to forests to restore damaged forests has increased China's forest area. This policy can not only increase the contributes of Chinese forest to mitigating climate change but also provided rich forest resource for researching. And this was one of the main reasons for article increasing. Except China, most of the countries with many articles were developed countries. Although some studies originated from developing countries, their number remains significantly lower compared to those from developed nations. To draw more robust and globally representative conclusions, increased research contributions from developing regions are essential.

Recent advances in forest soil carbon sequestration and GHG mitigation have been significantly shaped by research from leading institutions such as the Chinese Academy of Sciences, Zhejiang Agriculture and Forestry University, the United States Department of Agriculture (USDA), the Commonwealth Scientific and Industrial Research Organization (CSIRO), Griffith University, and the United States Forest Service and Commonwealth Scientific and Industrial Research Organization (Australia), the University of Florida. These institutions have played a pivotal role in expanding the scientific understanding of biochar's environmental behavior and its application in forest ecosystems.

Fundamental insights from scholars such as Johannes Lehmann and Stephen Joseph have clarified biochar's aromatic structure and physicochemical stability, distinguishing it from traditional charcoal and demonstrating its capacity to enhance long-term carbon retention in forest soils [49,77]. Field studies, such as those conducted in subtropical bamboo plantations, have shown that biochar application can significantly reduce soil heterotrophic respiration by increasing carbon recalcitrance and suppressing carbon-degrading microbial activity [78]. Global-scale assessments led by Lehmann and colleagues estimate that biochar systems could deliver annual greenhouse gas emission reductions of 3.4–6.3 Pg CO_2-equivalent, with approximately half attributed to carbon dioxide removal through biochar persistence in soils [26]. Recent studies have demonstrated that invasive weeds such as Crotalaria burhia and Eichhornia crassipes (water hyacinth) offer promising feedstocks for biochar production due to their high cellulose content, rapid growth, and ecological abundance. Optimization of pyrolysis conditions has yielded biochar with high fixed carbon, mesoporous structures, and nutrient-rich profiles, suitable for soil amendment and climate mitigation [79,80]. Collectively, these findings underscore the critical contribution of internationally recognized institutions and scholars in advancing biochar-based strategies for forest soil carbon sequestration and climate mitigation.

5. Conclusions

This bibliometric analysis offers a comprehensive synthesis of research trajectories in biochar application for forest soil carbon sequestration and greenhouse gas (GHG) mitigation from 1996 to 2025, highlighting a rapidly expanding and increasingly sophisticated field. The sustained rise in publication output, particularly from Chinese institutions, underscores the intensifying global commitment to nature-based climate solutions. Research emphasis has shifted from early explorations of "black carbon" toward nuanced, mechanism-oriented studies, with the "microbial community" now recognized as a central mediator of biochar's ecological effects. A broad consensus affirms biochar's capacity to enhance soil organic carbon (SOC) stocks; however, its variable influence on GHG fluxes necessitates integrated evaluations of net Global Warming Potential (GWP) to substantiate its climate mitigation efficacy.

Despite promising advances, several critical barriers remain, notably the paucity of long-term, landscape-scale field trials and the absence of standardized production protocols, both of which contribute to inconsistent outcomes across studies. To propel the field forward, future research must adopt a more integrative approach, emphasizing mechanistic investigations across diverse forest ecosystems. Equally essential is the implementation of comprehensive life cycle assessments that encompass not only soil carbon dynamics but also vegetation-mediated carbon sinks. Such holistic evaluations are vital for accurately quantifying biochar's climate benefits and for establishing robust, science-based standards to guide its deployment in sustainable forest management and global climate mitigation strategies.

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