West Science Agro
Vol. 4, No. 03, August 2026, pp. 318~329

Bibliometric Analysis of Biochar

Loso Judijanto
IPOSS Jakarta, Indonesia

Article Info

Article history:

Received Aug, 2026
Revised Aug, 2026
Accepted Aug, 2026

Keywords:

Biochar
Bibliometric Analysis
Vosviewer
Research Trends
Adsorption
Environmental Remediation

ABSTRACT

Biochar has emerged as a promising sustainable material with diverse applications in agriculture, environmental remediation, and carbon management. This study aims to investigate the global research development, intellectual structure, collaboration patterns, and emerging trends in biochar research through a bibliometric analysis approach. Scientific publications related to biochar were collected from a comprehensive academic database and analyzed using bibliometric techniques, including citation analysis, co-authorship analysis, institutional and country collaboration mapping, keyword co-occurrence analysis, thematic evolution analysis, and density visualization using VOSviewer. The findings reveal that biochar research has experienced substantial growth, with China and the United States representing the most influential contributors in terms of scientific productivity and international collaboration. Highly cited literature indicates that early research primarily focused on soil improvement, carbon sequestration, and agricultural sustainability, while recent studies have increasingly emphasized environmental applications, particularly adsorption, wastewater treatment, heavy metal removal, and engineered biochar development. Keyword analysis demonstrates that pyrolysis, adsorption, surface properties, and pollutant remediation have become central research themes, reflecting a transition toward advanced biochar technologies. This study highlights the multidisciplinary nature of biochar research and provides insights into future directions, including the development of modified biochar materials, circular economy applications, and sustainable environmental management strategies.

Corresponding Author:

Name: Loso Judijanto
Institution: IPOSS Jakarta
Email: losojudijantobumn@gmail.com

1. INTRODUCTION

The growing stress exerted on global environmental systems owing to climate change, soil erosion, resource depletion, and waste accumulation has prompted researchers and policy makers to look at sustainable options for managing the environment. Various solutions are being considered today and one that has received considerable interest is the use of biochar [1], [2]. Biochar is a carbon-rich material that results from the thermochemical process of biomass conversion under oxygen-depleted environments, mainly pyrolysis. As opposed to normal biomass decomposition, the process of pyrolysis allows the formation of carbon compounds that remain stable within the soils for decades to even centuries; thus biochar provides an effective way of sequestering carbon in the long term [3], [4]. Recent studies in biochar have not only focused on agriculture but also other fields including environmental engineering, energy generation, waste disposal and sustainable development.

Biochar has been applied in agriculture in some of the largest amounts due to the positive impact it can have on improving soil health and increasing yields of crops. Intensive agriculture, the use of high amounts of fertilizers, and destruction of lands have had negative effects on soil fertility and ecosystem resilience. Application of biochar was found to increase soil physical, chemical, and biological properties such as water retention, nutrient availability, microbiological activity, and organic carbon content in soil [5]. Moreover, biochar application decreases nutrient leaching and improves fertilizer efficiency, which contributes to more sustainable agricultural production systems. Several studies have found that effectiveness of biochar applications depends on different parameters including type of feedstock, production temperature, application rate, soil properties, and climate [6], [7].

In addition to agricultural uses, biochar has been widely appreciated for being an integral part of circular economy solutions. The agricultural, forestry, and municipal organic waste is usually associated with being an environmental problem due to improper handling leading to emissions of greenhouse gases. Conversion of the waste into biochar is a chance to turn low-value material into a high-value environmental asset. In such a way, the production of biochar fits into circular economy paradigm by enabling waste valorization, efficient use of resources, and carbon management [8]. Additionally, there has been research on the use of biochar technologies for the wastewater purification, pollutant removal, energy generation, and carbon-negative technology systems. A variety of biochar uses has led to the development of numerous scientific papers and technologies.

The function of biochar in mitigating climate change has intensified the interest in biochar research from academic and policy perspectives. Efforts made at the global level to reach the zero-net-emissions goal have drawn attention towards the role of negative emission technologies and nature-based solutions. Biochar has been recognized as a potential carbon dioxide removal technology since the stable carbon structures created through pyrolysis processes can lock the carbon present in the atmosphere into terrestrial ecosystems [9]. Besides, the creation of biochar can also lower greenhouse gas emissions related to biomass degradation and waste management systems. Nonetheless, the potential of biochar in mitigating climate change is constrained by technological, economic, and environmental factors, including the efficiency of the process, transportation needs, feedstock availability, and life cycle impacts [8]. Thus, an analysis of the historical trends of biochar research becomes relevant.

The fast growth of publications about biochar makes it difficult to determine the overall evolution and structure of the biochar research field. Literature review is useful for summarizing information on certain topics. However, literature reviews are mostly based on qualitative analysis and do not provide enough information about publication patterns, citation structures, collaboration networks, and trends of future researches in the area. Bibliometrics is a quantitative analysis method that is used to evaluate scientific literature through analyzing publication productivity, citations, author collaborations, networks of institutions, keywords, and intellectual structures of a research area [10]. In case of the biochar literature, bibliometric analysis will help in obtaining information on the overall evolution of the research field, topics that were most widely discussed, and perspectives for future research.

Despite the significant advancement in biochar research in recent years, the increased number of publications and their diversification posed challenges in terms of defining the body of knowledge and the development of the field. While several studies have addressed individual aspects of biochar such as soil amelioration, carbon sequestration, pollution reduction, and agricultural yield, there is still a need for comprehensive knowledge about trends in publishing, key players in research, research networks, theme development, and new areas. The lack of holistic review can hinder the ability of both researchers and policymakers in establishing research priorities and creating future biochar innovations. Thus, an evidence-based bibliometric analysis is needed in order to understand the intellectual structure of biochar research.

This research is intended to carry out an in-depth bibliometric analysis of biochar literature to examine publication patterns, influential publications, important authors, patterns of collaborations, and emerging themes of research in the area. Through using bibliometric methods, this study attempts to present an organized account of the development of scientific knowledge in biochar research and uncover the important areas in which biochar research has evolved. In addition, this study will attempt to uncover any research areas for the future through exploring keyword patterns, thematic clusters, and intellectual relationships among different publications. The results from this study are likely to be useful in understanding the development of biochar research.

2. METHODS

In this research, a bibliometric analysis method will be applied to analyze the development, structure, and evolution of research in biochar. The method of bibliometric analysis is a type of research based on quantitative measures, which use statistical tools and visualizations to study scientific publications with the aim to reveal publication patterns, citation patterns, influential authors, institutional involvement, collaboration in research, and emergent areas of knowledge [11]. This method has been chosen since the biochar research field has become a multidisciplinary one with involvement of environmental science, agriculture, engineering, chemistry, and sustainability. Thus, there is a considerable body of literature in this area.

Collection of data was done using the Scopus database, which is considered as one of the largest academic databases that have been used in the field of bibliometrics because of its wide coverage of scientific literature published in peer-reviewed journals. The search strategy was focused on retrieving scholarly works related to biochar using the following keywords "biochar" and "bio-char" in the title, abstract, and keywords. The retrieved records were selected using pre-defined inclusion and exclusion criteria in order to make sure about the quality of the dataset. Inclusion criteria included only scholarly articles that were published in peer-reviewed journals while conference papers, book chapters, editorials, and any other types of publications were excluded from the study. The dataset included bibliographic data including the year of publication, authors' information, institutions, countries, number of citations, keywords, and references.

Various bibliometric analyses were carried out in order to analyze the landscape of scientific research on biochar using VOSviewer software. These include publication trend analysis, citation trend analysis, co-authorship analysis, co-occurrence keyword analysis, and citation network analysis. Co-authorship analysis was done in order to look at the trends in researcher and country collaboration, while co-occurrence keyword analysis was used in order to look at the trends in research topics over time. Results from the analysis carried out in the visualizer allowed for the identification of research trends and the interrelationships of scientific terms. In this way, the current research gives a complete overview of the evolution of scientific literature related to biochar.

3. RESULT AND DISCUSSION

3.1 Co-Author Analysis

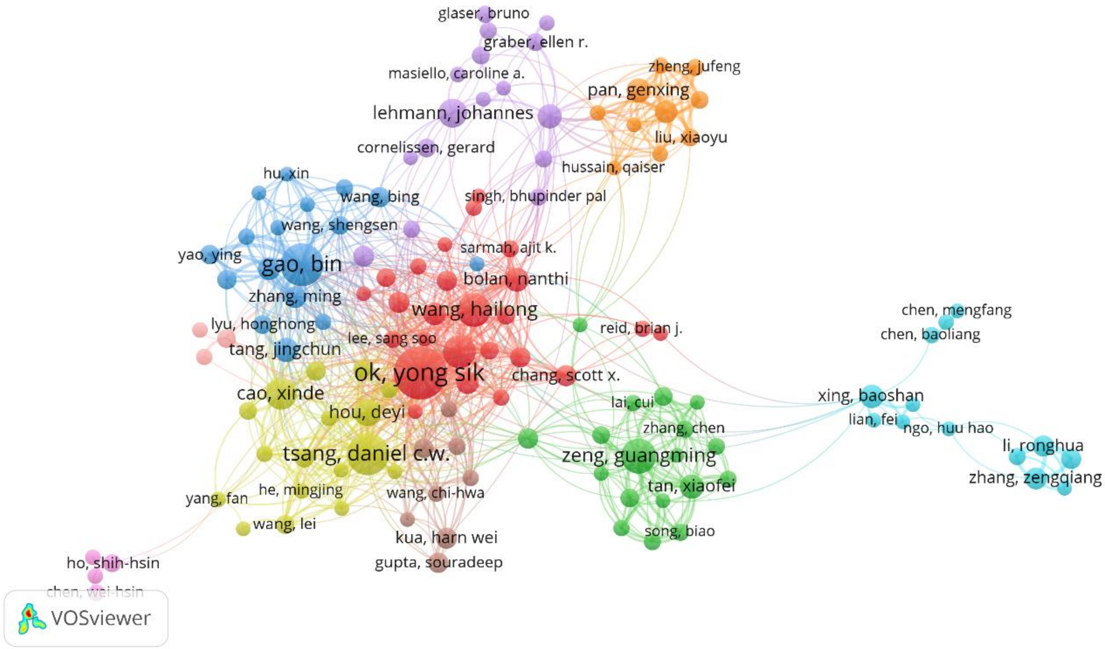

Figure 1. Author Visualization
Source: Data Analysis

The intellectual collaboration structure in biochar research is displayed in Figure 1 below. From the network, one can identify some clusters that are interconnected, meaning there exist many research teams working on various aspects of biochar research. The central place occupied by Wang, Hailong, Ok, Yong Sik, Gao, Bin, and Tsang, Daniel C.W. indicates the important role played by these individuals in biochar research due to their high connectivity. They are seen as important bridges connecting the different research groups. The red cluster where Wang Hailong and Ok Yong Sik are predominant is an important collaborative cluster with many interactions, showing their importance in advancing the research on biochar, especially in its environmental application and soil amendment. On the other hand, the blue cluster centered on Gao Bin is another important research stream.

Other clusters showcase specialized research collaboration networks. Green cluster with authors including Zeng Guangming, Tan Xiaofei, and Song Biao suggests the research area of environmental remediation and biochar treatment technologies. The yellow cluster, led by Tsang, Daniel C.W., includes studies on sustainable materials, pollutant removal and biochar interaction mechanisms with environmental systems. Purple and orange clusters by researchers such as Lehmann Johannes, Graber Ellen R., Pan Genxing, and Zheng Jufeng, denote the core research areas, including biochar production, carbon sequestration, carbon dynamics in soils and agricultural sustainability. In general, the network shows that biochar research has become a well-cooperated and interdisciplinary area, connecting environmental science, agriculture, materials engineering, and climate change mitigation. The intensive links between clusters suggest that future biochar research will continue to be focused on sustainable resource management and environmental restoration.

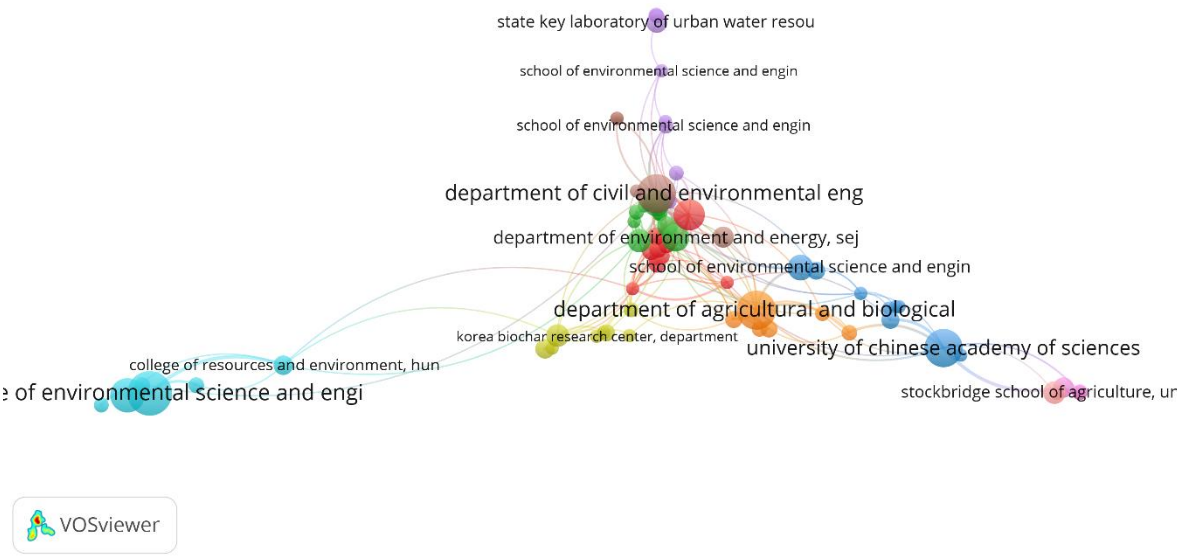

Figure 2. Institution Visualization
Source: Data Analysis

Figure 2 represents the distribution and connection pattern of the research organizations involved in worldwide biochar research. This network includes a number of institutional clusters, which suggests that there is a lot of cooperation between universities, research centers, and departments in the field of biochar research. There are three institutions, namely the Department of Civil and Environmental Engineering, the Department of Agricultural and Biological Engineering, and the University of Chinese Academy of Sciences, that emerge as important nodes of the network due to their size and connections with other nodes, thus playing an important role in biochar publications.

This network also shows the interdisciplinary research carried out in relation to biochar due to the participation of institutions from different sectors such as environmental science, energy systems, agriculture, and water resources. Clusters that involve institutions from the field of environmental engineering suggest the use of biochar for pollution control, water purification, and environmental management. On the other hand, institutions relating to agriculture suggest the use of biochar in soil management, carbon management, and sustainable agriculture. Organizations such as the Korea Biochar Research Center and the State Key Laboratory of Urban Water Resources and Environment also show that biochar research is being conducted in specialized fields.

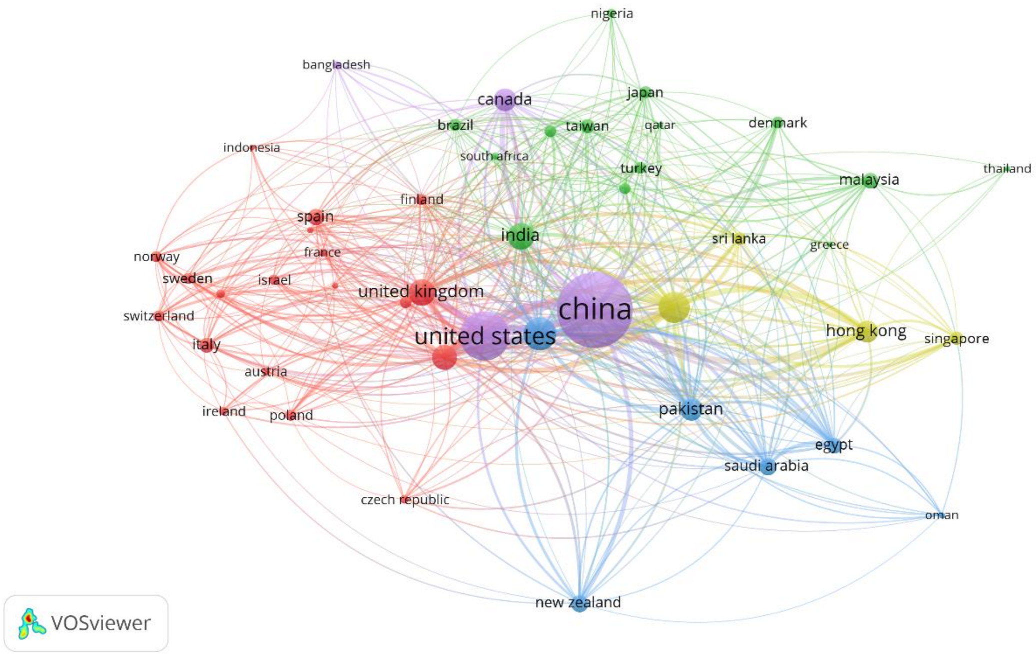

Figure 3. Country Visualization

Source: Data Analysis

Figure 3 demonstrates the global distribution and cooperation in biochar research. This graph indicates that China and the US are the most dominant and influential countries by having the biggest nodes, which show that these two countries are highly productive in terms of research and have a significant number of collaborative relations with other nations. China is in the center of the network with connections with many countries, showing the significant role of this country in the development of biochar in such fields as environmental remediation, agriculture, carbon handling, and sustainable technology. Another dominant country is the US, which is well-connected with researchers from Europe, Asia, and Oceania. Some other countries include India, the UK, Canada, Australia, Japan, and Germany.

Some of the collaborative patterns in different regions can be observed through the network analysis. The first cluster is represented in red color and consists of the countries that are located in Europe, such as United Kingdom, Spain, France, Italy, and Sweden. This implies the high level of collaboration among the countries located in Europe in the sphere of research associated with environmental sustainability and its applications. The second cluster is represented in green color and includes the countries from Asia and emerging economies like India, Japan, Malaysia, Thailand, and Turkey.

3.2 Citation Analysis

Table 1. Top Cited Literature

Citations	Authors and Year	Title
4710	[12]	Biochar effects on soil biota - A review
4398	[13]	Biochar as a sorbent for contaminant management in soil and water: A review
3074	[14]	Dynamic molecular structure of plant biomass-derived black carbon (biochar)
2696	[15]	Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects
2369	[16]	Sustainable biochar to mitigate global climate change

2241	[17]	Preparation, modification and environmental application of biochar: A review
2226	[18]	A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis
2202	[19]	Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review
2040	[20]	A review of biochar and its use and function in soil
2010	[21]	The forms of alkalis in the biochar produced from crop residues at different temperatures

Source: Scopus 2026

Table 1 shows the most cited publications in biochar studies according to the number of citations and describes the key scientific breakthroughs that have defined the progress in this area. The most cited paper, [22], "Biochar effects on soil biota – A review" with 4,710 citations, highlights the essential need for knowledge about interactions between biochar and soil ecosystems. It is followed by the highly cited paper, [13] with 4,398 citations, which pays attention to the application of biochar as a sorbent material for managing contaminants in soil and water. High citations show that at the early stages of biochar studies, researchers were interested in three key aspects: soil improvement, environmental remediation, and climate change mitigation. Publications by [23] and [20] draw attention to the possibilities of biochar in carbon sequestration and sustainable soil management, and papers by [19] and [24] to its usage in contaminant removal via adsorption mechanism. In addition, highly cited papers that study physicochemical properties, pyrolysis conditions, and feedstocks of biochar, like [15] and [25], show an increased interest of scientists in optimization of biochar production.

3.3 Keyword Co-Occurrence

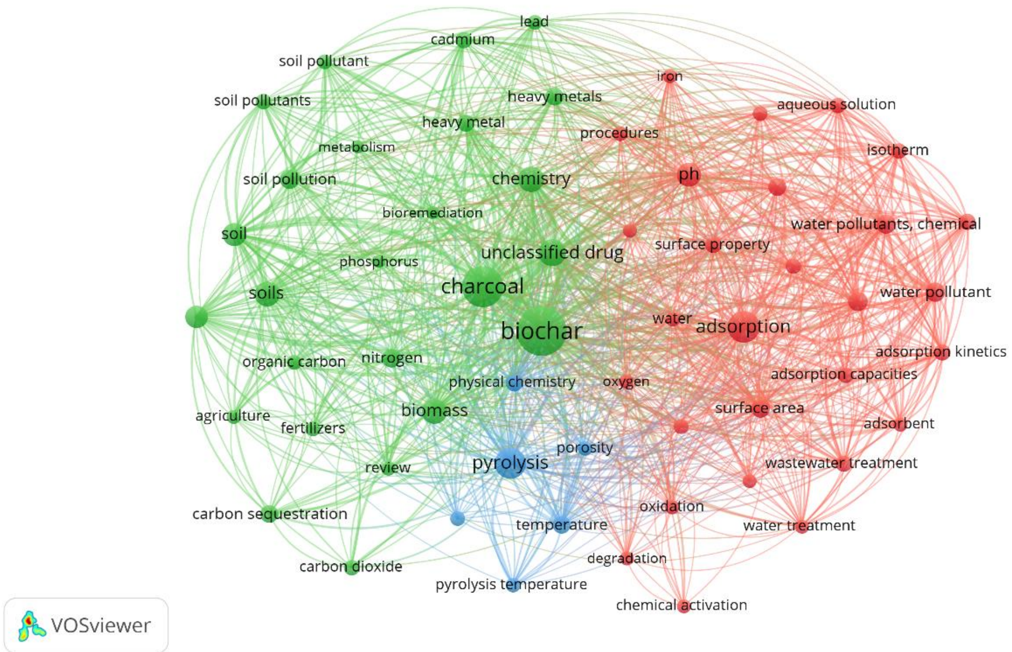

Figure 4. Network Visualization
Source: Data Analysis

The fourth figure shows the major themes and the underlying structure of global research on biochar. This network consists of several inter-connected clusters, thus showing that research on biochar has taken place in various scientific fields, especially environmental cleanup, soil science, and materials science. The term "biochar" serves as the central node having close connections with other key terms like "adsorption," "pyrolysis," "soil," "biomass," "water," and "charcoal." High connectivity of the term "biochar" implies that this term acts as a link among different research areas.

The red group denotes the main research theme of using biochar in removing pollutants and water treatments. Words like "adsorption," "water pollutant," "wastewater treatment," "adsorption capacity," "surface area," "surface property," and "adsorption kinetics" highlight that there is a lot of literature on the capability of biochar in adsorbing contaminants in aqueous media. These keywords show the significance of biochar as an effective adsorbent that is low cost and environmentally friendly for removing heavy metals, organic pollutants, and other chemical pollutants. Terms like "chemical activation," "oxidation," and "pH" show that there is a trend of using modifications to improve the capability of biochar in adsorption.

The cluster labeled green deals with the nexus of biochar, soil enrichment, agriculture, and environmental sustainability. The keyword phrases "soil," "soils," "soil pollution," "heavy metals," "agriculture," "fertilizers," "organic carbon," "carbon sequestration," and "carbon dioxide" show that a considerable amount of work is being done on how biochar can be used to improve the quality of the soil, clean it from pollution, and mitigate climate change. This cluster shows how biochar contributes to sustainable agricultural practice through nutrient availability, carbon sequestration in soils, and rehabilitation of depleted soils.

The blue cluster reflects work devoted to the processes of biochar production and physicochemical properties, especially biochar produced via pyrolysis technology. Words like "pyrolysis," "pyrolysis temperature," "temperature," "porosity," and "physical chemistry" show that the scientists examine the impact of conditions under which the biochar was produced on its properties and future application. The high correlation between the words "pyrolysis" and "adsorption" shows that the optimization of the process is very important for functional biochar properties.

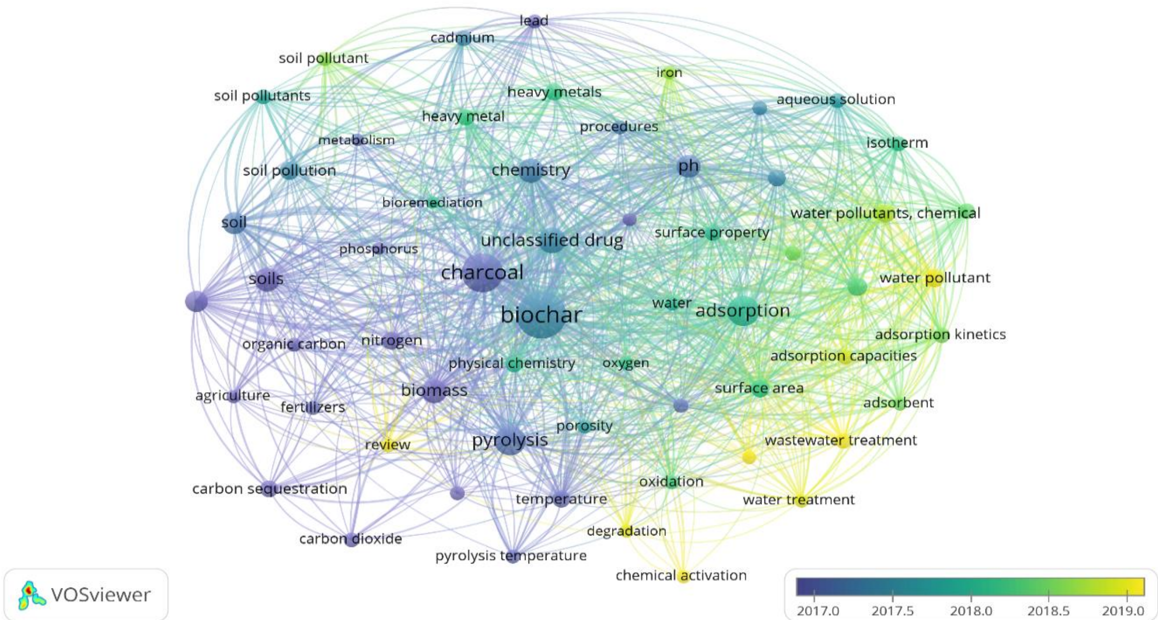

Figure 5. Overlay Visualization

Source: Data Analysis

Figure 5 depicts the timeline for the keyword trends in the biochar research area, whereby color denotes the average time span of keywords starting from early research trends (blue to purple) and recent research trends (green to yellow). The central location of “biochar” reflects its consistent importance as a research trend across the growth of research over time in association with key topics such as “adsorption,” “pyrolysis,” “soil,” “biomass,” and “water.” Darker colors for early research trends denote their linkages with basic aspects like soil enhancement, carbon sequestration, charcoal, biomass, and pyrolysis.

This is reflected in the use of terms such as “pyrolysis,” “temperature,” “porosity,” “surface area,” “physical chemistry,” and “adsorption,” which suggest that more research was directed towards understanding how different production conditions affect biochar properties and performance. This phase of development of the study of biochar saw the beginning of the exploration of the connection between the structure of biochar and its capability to interact with contaminants. The appearance of keywords like “heavy metals,” “soil pollution,” “bioremediation,” and “water treatment” denotes the widening of the application field of biochar beyond improving soil fertility.

Emerging research trends, which have been shown in green to yellow colors, indicate a greater inclination towards environmental applications involving pollutant removal and wastewater treatment. The key phrases like "adsorption kinetics," "adsorption capacities," "water pollutant," "wastewater treatment," "chemical activation," and "surface property" point out that the new directions in biochar research involve optimizing its performance through modification methods. It means that current researches on biochar tend to move from mere characterization to engineering better biochar for enhanced adsorption performance and application.

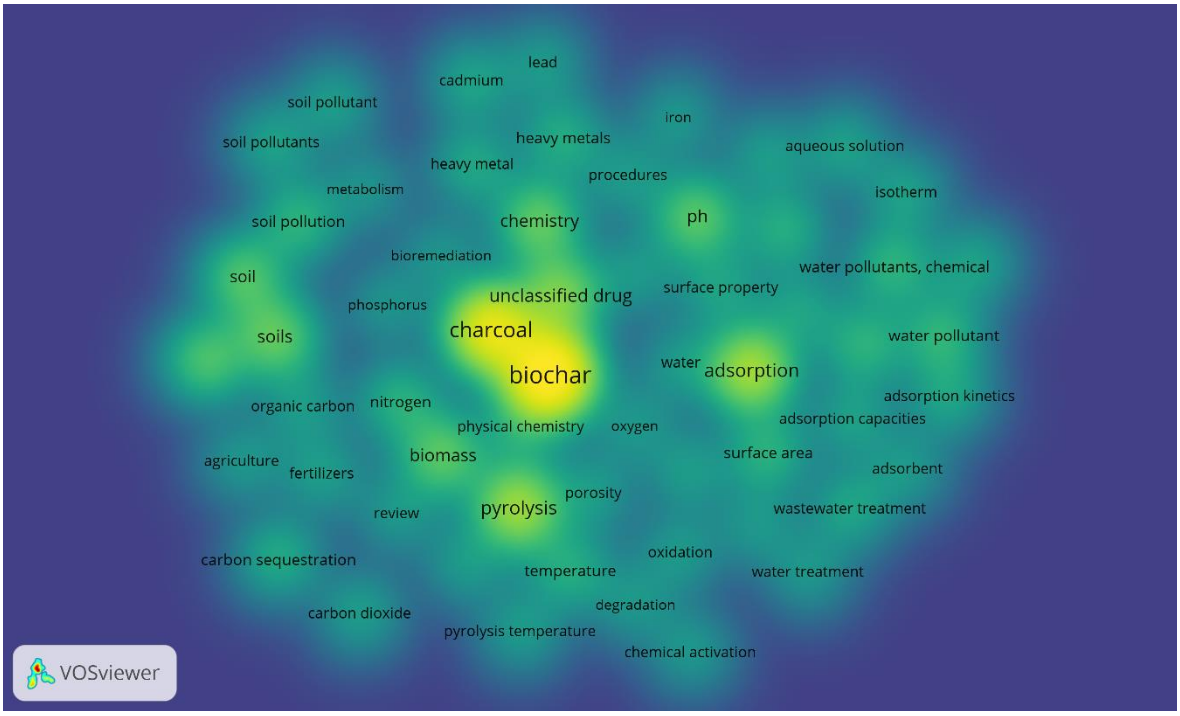

Figure 6. Density Visualization
Source: Data Analysis

The density and intensity of major research themes in the biochar literature have been demonstrated in Figure 6. The densest zone in the figure has been seen near the central keywords, which include “biochar,” “charcoal,” “pyrolysis,” and “adsorption.” Therefore, it can be seen that these research themes make up the fundamental knowledge structure of the field. The high intensity near the keyword "biochar" shows that biochar is the key research topic, which connects different fields of science such as material science, environmental engineering, and agriculture. The connection of biochar with pyrolysis reveals the importance of production methods on biochar, whereas its connection with adsorption suggests the significance of biochar as an efficient adsorbent material.

Other minor fields of research also become clear from the diagram, including soil treatment, carbon capture, heavy metals cleanup, wastewater treatment, and chemical activation. The density near words like "soil," "agriculture," "organic carbon," and "carbon dioxide" signifies an ongoing interest in the use of biochar to enhance soil properties and counter climate change by means of carbon storage. On the other hand, the cluster near words such as "water pollutant," "adsorption capacity," "surface area," and "chemical activation" signifies the rising trend of designing environmentally advanced biochar.

Discussion

The analysis shows that the field of biochar research has turned out to be highly interdisciplinary and fast-growing due to an increase in global interest in sustainable resource use, environmental protection, and climate change mitigation. The analysis of publication trends, citation patterns, and important literature reveals that at the beginning of the research on biochar, the emphasis was placed on studying the fundamentals of the material itself and its potential application for improving soil. Papers by [2], [7], [26] became milestones of biochar research by emphasizing its impact on soil ecology, carbon sequestration capacity, and sustainability of agriculture. Such foundational papers made a great contribution to the emergence of biochar as a multifunctional material capable of solving the problems of agriculture as well as the issues of environmental sustainability. The prevalence of China and the USA in the collaboration network also indicates their scientific leadership in biochar research due to big environment and technology studies.

As can be seen, there is a clear shift in biochar studies from traditional agriculture-related applications to more sophisticated techniques used for environmental remediation. Indeed, the high correlation of biochar with the terms such as adsorption, water treatment, heavy metals, wastewater treatment, and surface properties shows that pollutant removal is one of the key topics studied. It can be explained by the fact that highly cited articles deal with using biochar as a sorbent which efficiently removes pollutants both from soil and water bodies. Scientists started studying the impact of different factors (pyrolysis process parameters, type of material used as a feedstock, surface modifications, chemical activation) on biochar characteristics, proving the tendency to create artificial materials. The time analysis demonstrates this tendency very clearly as the latest works deal with making biochar more functional rather than studying its advantages.

Moreover, the cooperation and thematic patterns show that future investigations on biochar are likely to be carried out through further integration among environmental engineering, agriculture, chemistry, and materials science. The existence of highly-developed collaborative and international networks in institutions shows that biochar studies need multidisciplinary studies in order to deal with sustainability challenges. Some emerging themes concerning water treatment, carbon management, circular economy, and advanced adsorption techniques show that biochar can serve as a sustainable method for turning the waste of biomass into useful environmental products. Further research in this area must pay attention to the optimization of biochar production processes, application-specific modifications of biochar, and the practical implications of laboratory results.

4. CONCLUSION

This bibliometric study provides a comprehensive overview of the global development, intellectual structure, and emerging research directions of biochar studies. The findings demonstrate that biochar has evolved from an initially agriculture-focused research topic into a multidisciplinary field encompassing environmental remediation, material engineering, carbon management, and sustainable resource utilization. Citation analysis identified influential studies that established the importance of biochar for soil improvement, contaminant removal, and climate change mitigation, while collaboration analysis revealed the dominant contributions of countries, institutions, and researchers from China, the United States, and other leading scientific communities. Keyword and thematic analyses further indicate that current research trends are increasingly centered on adsorption technologies, wastewater treatment, heavy metal remediation, pyrolysis optimization, and engineered biochar development. These findings confirm that biochar plays an important role in supporting sustainable development through the conversion of biomass waste into valuable environmental solutions. Future research should focus on improving biochar production technologies, enhancing application-specific performance, and strengthening real-world implementation to maximize its contribution to circular economy practices and global sustainability challenges.

REFERENCES

[1] M. Senanayake, I. Harymawan, G. Dorfleitner, S. Lee, J. H. Rhee, and Y. S. Ok, "Toward More Nature-Positive Outcomes: A Review of Corporate Disclosure and Decision Making on Biodiversity," *Sustain.*, vol. 16, no. 18, 2024, doi: 10.3390/su16188110.

[2] J. Lee, Y. F. Tsang, S. Kim, Y. S. Ok, and E. E. Kwon, "Energy density enhancement via pyrolysis of paper mill sludge using CO2," *J. CO2 Util.*, vol. 17, pp. 305–311, 2017, doi: 10.1016/j.jcou.2017.01.001.

[3] T. R. K. C. Doddapaneni and T. Kikas, "Advanced Applications of Torrefied Biomass: A Perspective View," *Energies*, vol. 16, no. 4, 2023, doi: 10.3390/en16041635.

[4] X. Xiong, R. Jiang, B. Deng, J. Yang, and D. Wang, "Bionic Structural Design and Electrochemical Manufacture of WC/N-Doped Carbon Hybrids as Efficient ORR Catalyst," *J. Electrochem. Soc.*, vol. 167, no. 6, 2020, doi: 10.1149/1945-7111/ab7b82.

[5] Z. Ginting, A. Setiawan, K. Anshar, I. Ibrahin, I. R. Hasanah, and Z. Fazira, "Optimization of the production of grade A liquid smoke from Patchouli solid residue using a distillation-adsorption process," *AIMS Environ. Sci.*, vol. 12, no. 1, pp. 106–119, 2025, doi: 10.3934/environsci.2025005.

[6] A. G. Choudhury, P. Roy, S. Kumari, and V. K. Singh, "Utility of Fruit-Based Industry Waste," *Handbook of Solid Waste Management: Sustainability through Circular Economy*. Springer Nature, Department of Fruit Science (Fruit Breeding), Horticulture College, Khuntpani, Chaibasa, Birsa Agricultural University, Jharkhand, Ranchi, India, pp. 757–784, 2022. doi: 10.1007/978-981-16-4230-2_38.

[7] E. Naushad, S. S. Chandraraj, I. Suyambulingam, and D. Divakaran, "Comprehensive Review on Eco-Friendly Fillers 2012–2023: A Potential Resource for Polymer Composites," *Springer Proceedings in Materials*, vol. 60. Springer, Department of Chemistry, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, 600062, India, pp. 423–462, 2024. doi: 10.1007/978-981-97-7071-7_31.

[8] M. Wehbe, J. Kazzi, R. Dgheim, and M. El Bachawati, "Modeling the aerobic conversion process of organic waste into organic fertilizers using Aspen HYSYS," in *E3S Web of Conferences*, Z. E., Ed., Department of Chemical Engineering, University of Balamand, Tripoli, 100, Lebanon: EDP Sciences, 2024. doi: 10.1051/e3sconf/202458509010.

[9] M. Senanayake, F. K. G. Putra, R. P. Gregory, I. Harymawan, J. H. Rhee, and Y. S. Ok, "From biodiversity to ESG: evaluating disclosure approaches of companies operating in Indonesia," *Front. Sustain.*, vol. 6, 2026, doi: 10.3389/frsus.2025.1668560.

[10] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *J. Bus. Res.*, vol. 133, pp. 285–296, 2021.

[11] A. Halibas, U. Akram, A.-P. Hoang, and M. D. Thi Hoang, "Unveiling the future of responsible, sustainable, and ethical consumption: a bibliometric study on Gen Z and young consumers," *Young Consum.*, vol. 26, no. 7, pp. 142–171, 2025, doi: 10.1108/YC-11-2024-2327.

[12] J. Lehmann, M. C. Rillig, J. Thies, C. A. Masiello, W. C. Hockaday, and D. Crowley, "Biochar effects on soil biota - A review," *Soil Biol. Biochem.*, vol. 43, no. 9, pp. 1812–1836, 2011, doi: 10.1016/j.soilbio.2011.04.022.

[13] M. Ahmad *et al.*, "Biochar as a sorbent for contaminant management in soil and water: A review," *Chemosphere*, vol. 99, pp. 19–33, 2014, doi: 10.1016/j.chemosphere.2013.10.071.

[14] M. Keiluweit, P. S. Nico, M. Johnson, and M. Kleber, "Dynamic molecular structure of plant biomass-derived black carbon (biochar)," *Environ. Sci. Technol.*, vol. 44, no. 4, pp. 1247–1253, 2010, doi: 10.1021/es9031419.

[15] A. Tomczyk, Z. Sokołowska, and P. Boguta, "Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects," *Rev. Environ. Sci. Biotechnol.*, vol. 19, no. 1, pp. 191–215, 2020, doi: 10.1007/s11157-020-09523-3.

[16] D. Woolf, J. E. Amonette, F. A. Street-Perrott, J. Lehmann, and S. Joseph, "Sustainable biochar to mitigate global climate change," *Nat. Commun.*, vol. 1, no. 5, 2010, doi: 10.1038/ncomms1053.

[17] J. Wang and S. Wang, "Preparation, modification and environmental application of biochar: A review," *J. Clean. Prod.*, vol. 227, pp. 1002–1022, 2019, doi: 10.1016/j.jclepro.2019.04.282.

[18] S. Jeffery, F. G. A. Verheijen, M. van der Velde, and A. C. Bastos, "A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis," *Agric. Ecosyst. Environ.*, vol. 144, no. 1, pp. 175–187, 2011, doi: 10.1016/j.agee.2011.08.015.

[19] D. Mohan, A. Sarswat, Y. S. Ok, and C. U. Pittman, "Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review," *Bioresour. Technol.*, vol. 160, pp. 191–202, 2014, doi: 10.1016/j.biortech.2014.01.120.

[20] S. P. Sohi, E. Krull, E. Lopez-Capel, and R. Bol, "A review of biochar and its use and function in soil," *Advances in Agronomy*, vol. 105, no. 1. Academic Press Inc., School of GeoSciences, University of Edinburgh, Edinburgh, United Kingdom, pp. 47–82, 2010. doi: 10.1016/S0065-2113(10)05002-9.

[21] J.-H. Yuan, R.-K. Xu, and H. Zhang, "The forms of alkalis in the biochar produced from crop residues at different temperatures," *Bioresour. Technol.*, vol. 102, no. 3, pp. 3488–3497, 2011, doi: 10.1016/j.biortech.2010.11.018.

[22] J. Lehmann *et al.*, "Biochar in climate change mitigation," *Nat. Geosci.*, vol. 14, no. 12, pp. 883–892, 2021, doi: 10.1038/s41561-021-00852-8.

[23] D. Woolf, J. Lehmann, S. Ogle, A. W. Kishimoto-Mo, B. McConkey, and J. Baldock, "Greenhouse Gas Inventory Model for Biochar Additions to Soil," *Environ. Sci. Technol.*, vol. 55, no. 21, pp. 14795–14805, 2021, doi: 10.1021/acs.est.1c02425.

[24] H. Wang, H. Wang, H. Zhao, and Q. Yan, "Adsorption and Fenton-like removal of chelated nickel from Zn-Ni alloy electroplating wastewater using activated biochar composite derived from Taihu blue algae," *Chem. Eng. J.*, vol. 379, 2020, doi: 10.1016/j.cej.2019.122372.

[25] M. Keiluweit, M. Kleber, M. A. Sparrow, B. R. T. Simoneit, and F. G. Prahl, "Solvent-extractable polycyclic aromatic hydrocarbons in biochar: Influence of pyrolysis temperature and feedstock," *Environ. Sci. Technol.*, vol. 46, no. 17, pp. 9333–9341, 2012, doi: 10.1021/es302125k.

[26] S. S. Chopra *et al.*, "Navigating the Challenges of Environmental, Social, and Governance (ESG) Reporting: The Path to Broader Sustainable Development," *Sustain.*, vol. 16, no. 2, 2024, doi: 10.3390/su16020606.