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WOOD WASTE TO BIOFERTILIZER: A BIBLIOMETRIC ANALYSIS OF BIOCHAR APPLICATIONS IN SOIL ENHANCEMENT - TURNING WASTE INTO VALUABLE RESOURCES

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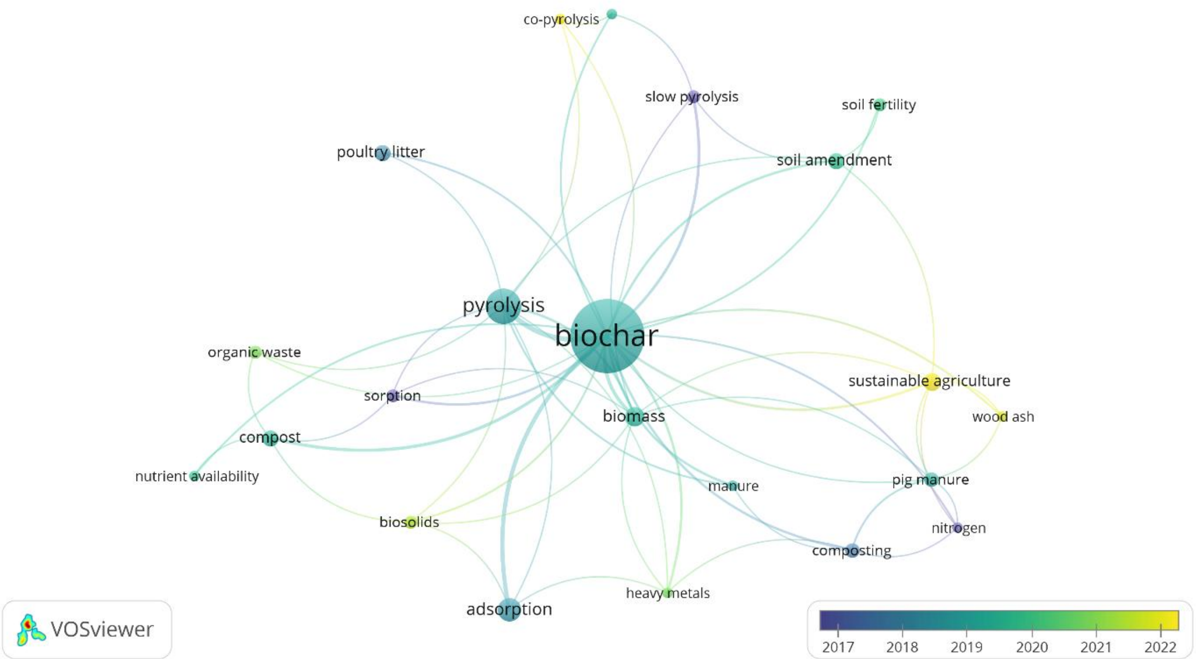
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Wood waste biochar shows strong potential as a sustainable biofertilizer.
- Global publications on this topic have increased steadily since 2010.
- China and the USA lead research output and international collaborations.
- Pyrolysis conditions strongly influence biochar nutrient performance.
- Future studies must link lab results with real field applications

ABSTRACT

This study presents a comprehensive bibliometric analysis of research trends and knowledge structures related to the application and valorization of wood waste biochar for biofertilizer. Utilizing the Scopus database, known for its extensive multidisciplinary coverage and indexing consistency, this analysis aims to systematically map the global research landscape, identify prolific contributors, core journals, dominant keywords, and knowledge gaps in the field. A total of 318 relevant documents published between 2000 and 2023 were analyzed using VOS viewer and bibliometric indicators, including publication output, country collaboration, co-citation networks, and keyword co-occurrence. The results reveal a consistent upward trajectory in publication volume, especially after 2015, indicating increasing scholarly interest in sustainable soil enhancement through biochar. China, the United States, and India emerged as the leading contributors, often collaborating on interdisciplinary projects. Core journals such as Bioresource Technology, Chemosphere, and Science of the Total Environment dominated citations and total link strength. Keyword co-occurrence analysis highlighted major thematic clusters, including pyrolysis, soil amendment, composting, nutrient retention, and heavy metal remediation, confirming biochar's versatility in agro-environmental applications. Despite strong foundational research, the network view map generated by VOS viewer revealed fragmented clusters with limited interconnectivity between certain keywords—indicating a lack of integration between specialized subfields such as nutrient cycling, biochar functionalization, and waste valorization. Overlay visualization also revealed that emerging topics like co-pyrolysis, wood ash, and urine-based fertilizer recovery have only recently gained attention, offering fertile ground for future exploration. Future research is recommended to focus on (i) enhancing the linkage between experimental and field-scale studies, (ii) integrating underrepresented keywords such as nutrient availability, biosolids, and co-pyrolysis, and (iii) adopting a systems-based approach for evaluating biochar's role across the soil–plant–microbe continuum. Furthermore, optimization of production and application parameters through multidisciplinary collaboration can advance biochar from lab-scale promise to real-world sustainability impact.

Keywords: Wood waste biochar; Biofertilizer; Bibliometric analysis; Sustainable agriculture; Co-pyrolysis; Nutrient cycling

1. Introduction

The ever-growing demand for wood products has led to the generation of substantial amounts of wood waste globally [1-3]. This wood waste, often seen as a byproduct of logging, sawmilling, and other wood-processing activities, poses significant environmental challenges [4-7]. Estimates suggest that millions of tons of wood waste are produced annually, with a considerable portion ending up in landfills or incinerated, contributing to pollution and greenhouse gas emissions [8-10]. Proper management and repurposing of this abundant resource are crucial not only for reducing environmental impact but also for tapping into its potential value in various applications.

In recent years, the trend towards sustainable agriculture has gained significant momentum, driven by the need to reduce the environmental footprint of agricultural practices and ensure food security [1-3, 11, 12]. This shift is characterized by the increasing use of biomass, including wood waste, as a sustainable resource. The conversion of organic waste into biochar through pyrolysis is an innovative solution that aligns with the principles of sustainable agriculture. Biochar, a stable, carbon-rich material, offers a range of benefits that make it an attractive option for enhancing soil health and productivity while also addressing waste management issues [13, 14].

The application of wood waste biochar in sustainable agriculture offers numerous benefits. Biochar improves soil structure, enhancing its porosity and water retention capacity, which is particularly beneficial in arid and semi-arid regions [15-17]. It also increases the availability of essential nutrients to plants by improving cation exchange capacity and reducing nutrient leaching. Furthermore, biochar acts as a habitat for beneficial soil microorganisms, promoting soil biodiversity and health [13, 18, 19]. Importantly, biochar sequesters carbon in the soil, contributing to climate change mitigation by reducing atmospheric carbon dioxide levels [20-22]. These multifaceted benefits underscore the potential of wood waste biochar to significantly contribute to sustainable agricultural practices.

Given the diverse benefits and increasing interest in wood waste biochar, it is essential to systematically analyse the research landscape in this field. Bibliometric reviews are invaluable for this purpose, providing a systematic and quantitative analysis of scientific publications [23-26]. They help identify key research areas, influential studies, and leading researchers and institutions [23, 27, 28]. By examining publication trends, citation networks, and research hotspots, bibliometric reviews can highlight emerging trends and knowledge gaps, guiding future research and policy-making [29-31]. Understanding these trends is crucial for optimizing the application of biochar in agriculture and maximizing its environmental and economic benefits.

The objective of this study is to conduct a comprehensive bibliometric analysis of the application and valorisation of wood waste biochar as a biofertilizer in soil enhancement. This review aims to map the current research landscape, identify key trends and developments, and highlight the contributions of leading researchers and institutions. By synthesizing the findings from existing literature, this study seeks to provide valuable insights into the potential of wood waste biochar to transform agricultural waste into valuable resources. Ultimately, this study aims to promote sustainable agriculture and environmental conservation by leveraging the benefits of biochar technology.

2. Methodology of Review

To conduct a comprehensive bibliometric analysis of the application and valorisation of wood waste biochar as a biofertilizer in soil enhancement, a structured methodology was employed using the Scopus database, known for its extensive coverage of scientific literature across various disciplines. Scopus was selected as the sole database for this bibliometric analysis due to its comprehensive coverage of peer-reviewed literature and its robust indexing of multidisciplinary research, particularly in environmental science, engineering, and agricultural applications. Its advanced filtering tools and reliable citation tracking make it ideal for identifying influential publications, mapping research trends, and analysing collaboration networks within the biochar research domain. The search strategy was designed to capture publications that include specific keywords related to the topic. The query used was TITLE-ABS-KEY (wood AND waste) AND TITLE-ABS-KEY (biochar) AND TITLE-ABS-KEY (fertilizer). This ensured the retrieval of relevant documents that mention these keywords in their titles, abstracts, or keywords. The search timeframe spanned from 2010, when the first paper on this topic was published, to the present.

The search resulted in a total of 138 documents. These documents were categorized by type, including 112 articles, 13 reviews, 8 conference papers, 4 book chapters, and 1 data paper. This categorization provided a clear overview of the types of publications contributing to the field. Further classification of the collected papers by subject area revealed a wide range of disciplines involved, underscoring the interdisciplinary nature of the topic. The documents were distributed across various subject areas, with Environmental Science leading at 82 documents, followed by Agricultural and Biological Sciences with 38, Energy with 34, Engineering with 21, and Chemical Engineering with 18. Other subject areas included Chemistry (13), Biochemistry, Genetics and Molecular Biology (8), Business, Management and Accounting (6), Materials Science (6), Medicine (6), Multidisciplinary (5), Earth and Planetary Sciences (4), Social Sciences (4), Computer Science (3), Economics, Econometrics and Finance (3), Immunology and Microbiology (3), Mathematics (2), Pharmacology, Toxicology and Pharmaceutics (2), Physics and Astronomy (2), Nursing (1), and Veterinary (1).

The bibliometric analysis involved several steps. Firstly, the distribution of documents by type and subject area was examined to understand the research landscape's scope and focus. Publication trends were analysed by reviewing the number of publications per year to identify growth patterns and trends in research on wood waste biochar as a biofertilizer. Citation metrics were employed to identify highly cited papers and influential authors, institutions, and journals. Network analysis, including co-authorship and keyword co-occurrence networks, was conducted to visualize collaboration patterns and research themes. Finally, thematic analysis of abstracts and keywords provided insights into key research topics, methodologies, and findings within the collected literature.

By combining these analytical approaches, the study offered a comprehensive overview of the research landscape, highlighting key contributions, emerging trends, and areas for future research in the application and valorisation of wood waste biochar as a biofertilizer. This methodology ensures a systematic and thorough examination of existing literature, providing valuable insights for researchers, policymakers, and practitioners interested in the sustainable use of wood waste biochar in agriculture.

3. Data Analysis and Visualisation of Wood Waste Biochar to Biofertilizer

3.1. Yearly Output of Scholarly Publications Related Wood Waste Biochar to Biofertilizer

The analysis of the yearly output of scholarly publications provides valuable insights into the research trends and growing interest in the field of wood waste biochar as a biofertilizer. Understanding the temporal distribution of publications allows us to identify key periods of increased research activity, emerging trends, and potential factors driving the interest in this sustainable agricultural practice. This section presents a detailed examination of the number of scholarly publications on this topic over the years, highlighting significant milestones and developments. Since the first paper on wood waste biochar as a biofertilizer appeared in 2010, there has been a noticeable increase in research output. This growth reflects the increasing recognition of biochar's potential benefits for soil enhancement and sustainable agriculture. The rising number of publications over the years indicates a growing awareness and interest among researchers, policymakers, and practitioners in exploring and utilizing wood waste biochar for agricultural applications. By analysing the yearly output, we can identify periods of accelerated research activity, which may correspond to advancements in biochar production technologies, increased funding for sustainable agriculture research, or heightened environmental awareness. Additionally, this analysis helps to pinpoint years with significant contributions to the literature, showcasing influential studies and landmark findings that have shaped the current understanding of wood waste biochar's role in soil enhancement.

The data presented in Figure 1 showcases the yearly trends in research output on the topic of wood waste biochar as a biofertilizer from 2010 to 2024. The figure highlights the number of scholarly publications produced each year, reflecting the growing interest and research activity in this field. From 2010 to 2011, the research output was minimal, with only one publication each year. This period marks the initial exploration phase of wood waste biochar applications in biofertilizers. In 2012 and 2013, the number of publications doubled to two per year, indicating a slight increase in research interest. A more noticeable growth in research output begins in 2014, with four publications, followed by a significant rise in 2015 with nine publications. The upward trend continues in 2016, reaching 11 publications, and although there is a slight dip to eight publications in 2017, the overall trajectory remains positive. The year 2018 sees a small increase to nine publications, but it is in 2019 that the field experiences a substantial surge, with 20 publications. This peak marks a period of heightened research activity and likely reflects significant advancements and increased funding in the study of wood waste biochar for biofertilizer applications.

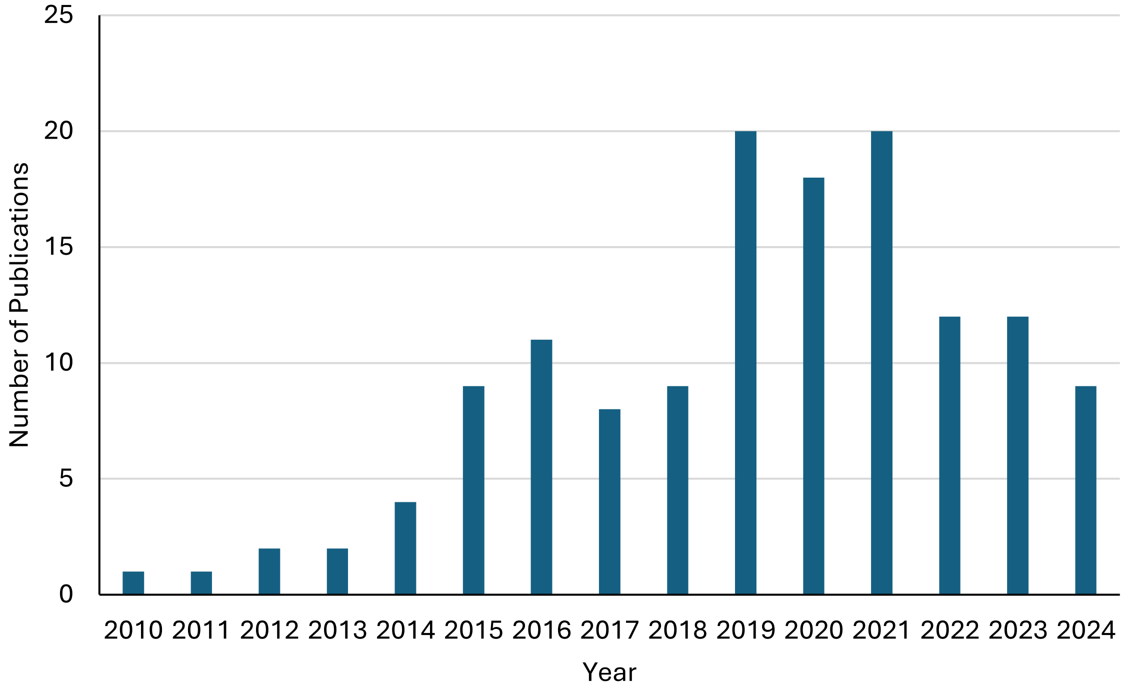


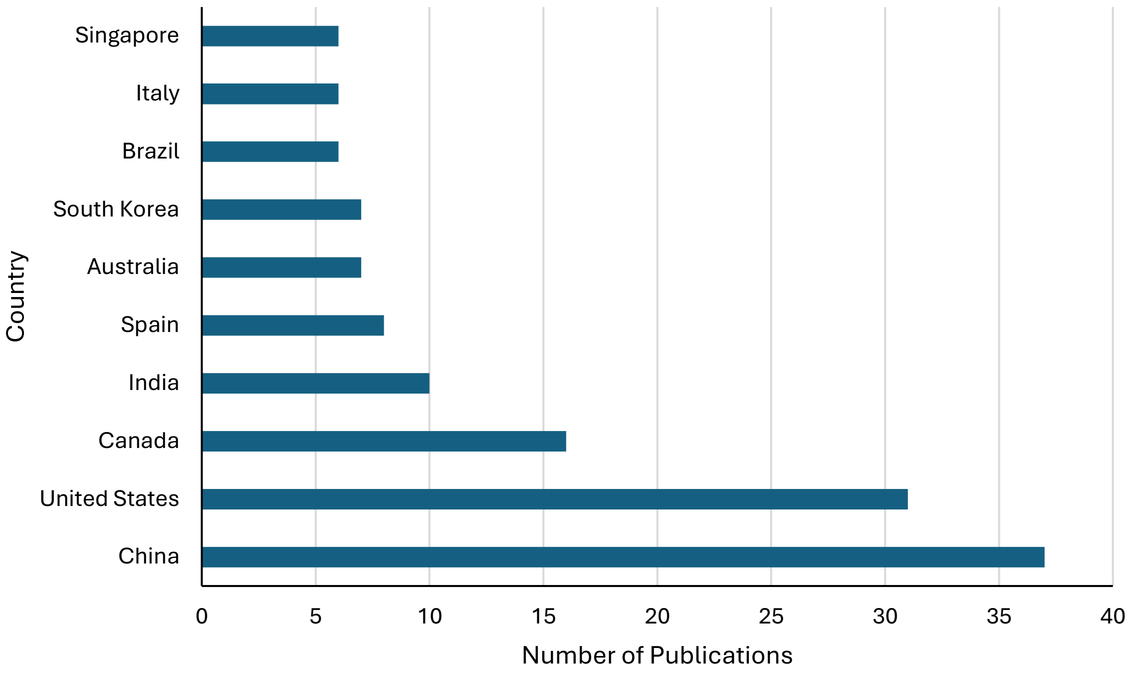
Figure 1. Yearly trends in research output on wood waste to biofertilizer

In 2020, the research output slightly decreases to 18 publications, maintaining a high level of activity. The year 2021 sees another peak, matching 2019 with 20 publications. This sustained interest demonstrates the continued importance and relevance of the topic in the scientific community. The subsequent years, 2022 and 2023, each have 12 publications, showing a consistent level of research output. The year 2024, although not yet complete, already has nine publications, suggesting that the interest in this research area remains strong. Overall, the data in Figure 1 illustrates a clear trend of increasing research output on wood waste biochar as a biofertilizer, with significant growth periods and sustained interest over the years. This trend highlights the expanding recognition of the potential benefits and applications of wood waste biochar in sustainable agriculture.

3.2. Geographical Analysis and Collaboration Countries of Research Publications on Wood Waste Biochar to Biofertilizer

Figure 2 provides a comprehensive overview of the geographical distribution and collaboration patterns of research publications related to wood waste biochar as a biofertilizer. The bar chart in Figure 2(a) illustrates the number of publications by corresponding author affiliations in various countries. It highlights that China leads the research output with 37 publications, demonstrating a strong focus on the application of wood waste biochar in sustainable agriculture within the country. The United States follows closely with 31 publications, indicating significant research activity and interest in biochar technologies. Canada, with 16 publications, reflects its commitment to environmental sustainability and innovative agricultural practices. India has 10 publications, showing growing interest and research efforts in utilizing biochar for soil enhancement. Other notable contributors include Spain (8 publications), Australia (7 publications), South Korea (6 publications), Brazil (5 publications), Italy (5 publications), and Singapore (5 publications).

The world map in Figure 2(b) visualizes the regional dispersion of research publications on wood waste biochar as a biofertilizer. The colour coding indicates the number of publications from each country, with darker colours representing higher publication counts. The map highlights several regional trends. In Asia, China and India are prominent contributors, with China being the leading nation in terms of research output. Other Asian countries like South Korea and Singapore also show notable contributions. In North America, the United States and Canada are major research hubs, reflecting significant scientific activity and collaboration in the field of biochar technology. In Europe, Spain and Italy are key contributors, with other European nations also participating in biochar research, indicating a widespread interest across the continent. In South America, Brazil emerges as a leading nation, showcasing the region's engagement with biochar applications in agriculture. Australia, with a significant number of publications, reflects its active research community focused on sustainable agricultural practices. Overall, this geographical analysis highlights the global interest and collaborative efforts in advancing the application of wood waste biochar as a biofertilizer. The data underscores the importance of international cooperation in addressing environmental challenges and promoting sustainable agriculture practices worldwide.



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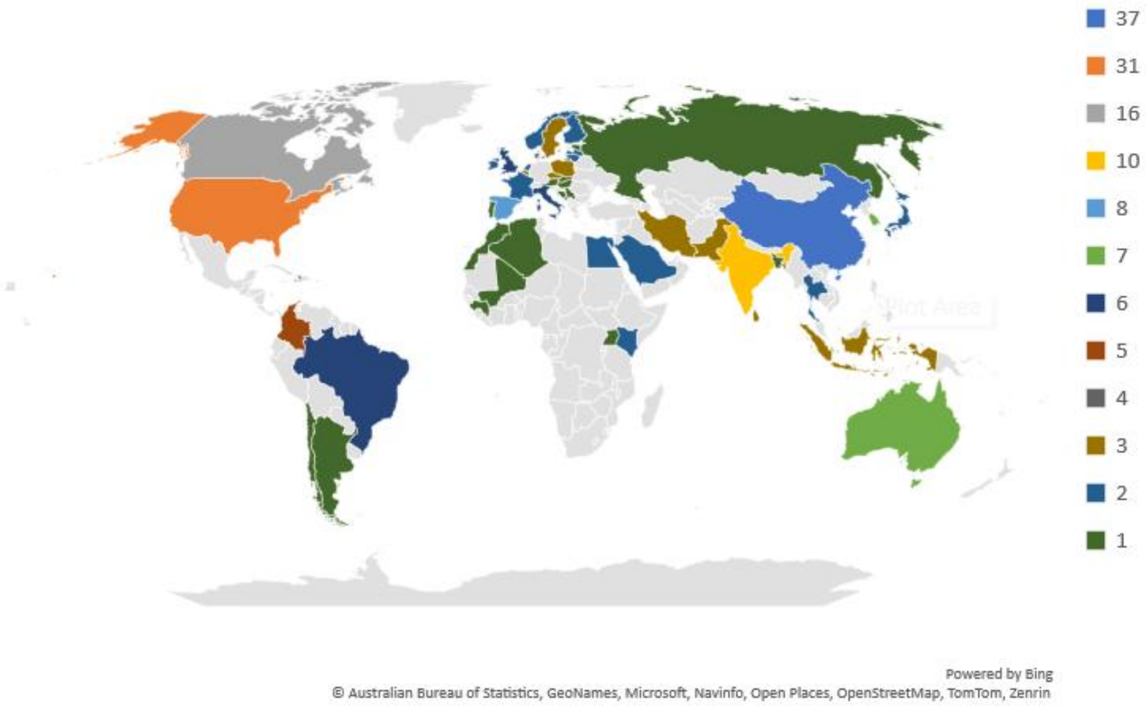


(b)

Figure 2. (a) The most prolific nations by corresponding author affiliations and (b) regional dispersion of publications on wood waste biochar to biofertilizer

Figure 2 provides a comprehensive view of the global research landscape on garlic extract for fungicidal applications. Part 2(a) highlights the most prolific nations based on the affiliations of corresponding authors, indicating the leading contributors to this field. India emerges as the dominant nation, with 53 publications, underscoring its significant research focus on the use of garlic extract as a natural fungicide. Pakistan follows with 14 publications, demonstrating a strong regional interest. Brazil ranks third with 11 publications, reflecting substantial contributions from South America. Egypt, with 8 publications, indicates a notable research presence in North Africa. Poland, Saudi Arabia, and the United States each contribute 5 publications, showing a moderate level of research activity. Argentina, Italy, and Malaysia each have 4 publications, highlighting their engagement in this area of study.

Part 2(b) of the figure illustrates the regional dispersion of publications through a world map, showcasing the geographical spread of research efforts. The map reveals a concentrated research activity in South Asia, particularly in India and Pakistan, which are the top contributors. Brazil's significant contribution places South America as another key region in this research domain. North America, represented by the United States, and Europe, with notable contributions from Poland and Italy, also show substantial research outputs. In the Middle East, Saudi Arabia stands out as a significant contributor. The map also highlights contributions from various other regions, including Australia (2 publications), Mexico (2 publications), and several countries in Africa and Asia with smaller publication counts, such as Nigeria, Kenya, Japan, and China (each with 1 publication).

This geographical analysis underscores the widespread recognition of garlic extract's potential as a natural fungicide and reflects a diverse global interest. The varying levels of research activity across different regions highlight both well-established research hubs and emerging areas of interest, suggesting opportunities for increased international collaboration and knowledge sharing. The map also indicates potential gaps in the research landscape, where further exploration and development could be beneficial, particularly in regions with fewer publications. Overall, the data presented in Figure 2 highlights the global engagement in exploring sustainable agricultural practices through the Wood Waste Biochar to Biofertilizer

Figure 3 illustrates the co-author network for countries engaged in research on wood waste biochar as a biofertilizer, with a threshold set at a minimum of three collaborations and showing a total of 33 links. This network analysis provides valuable insights into the collaborative patterns and key international partnerships within this research domain. Table 1 provides a comprehensive overview of research contributions from various countries in the domain of wood waste biochar as a biofertilizer. China leads the field with 37 documents, receiving a total of 2060 citations, indicating the significant impact and recognition of Chinese research. China also has the highest total link strength of 28, showcasing extensive international collaboration. The United States follows closely with 31 documents and 2057 citations, and a strong collaborative network reflected in a total link strength of 19. Canada has published 16 documents, receiving 914 citations, with a total link strength of 18, suggesting substantial international collaboration. South Korea and Australia have both published 7 documents. South Korea received 956 citations and has a link strength of 8, while Australia garnered 783 citations with a link strength of 9. Singapore and the United Kingdom each contributed 6 documents, with Singapore receiving 348 citations and a link strength of 7, and the United Kingdom receiving 213 citations and a link strength of 2. Spain has 8 publications with 1177 citations and a link strength of 6, reflecting its significant research impact and collaborations. Brazil contributed 6 documents with 508 citations and a link strength of 4, indicating moderate collaboration.

Other notable contributors include India with 10 documents and 93 citations, Pakistan with 3 documents and 199 citations, and Colombia with 5 documents and 99 citations. These countries show varying degrees of collaboration, as indicated by their respective link strengths. Countries like the Czech Republic, Poland, Sri Lanka, Sweden, Denmark, Indonesia, and Iran have contributed fewer documents (ranging from 2 to 4) but still play a role in the global research network, as indicated by their citations and link strengths. Overall, Table 1 highlights the significant contributions and collaborative efforts of various countries in advancing research on wood waste biochar as a biofertilizer. The data underscores the importance of international cooperation in enhancing the impact and dissemination of scientific knowledge in this field.

Figure 3(a) illustrates the co-author network for countries involved in research on wood waste biochar as a biofertilizer, with a threshold set at a minimum of three collaborations, resulting in a total of 33 links. Each node represents a country, and the size of the node reflects the number of publications from that country. The links between nodes indicate collaborative relationships, with thicker lines denoting stronger or more frequent collaborations. This network analysis highlights the strength and extent of international partnerships in this research domain. The United States emerges as a central node with the most extensive network, indicating its significant role in international collaborations. The United States shows strong connections with countries such as Brazil, the United Kingdom, and Mexico. These robust links suggest that the United States has been a major hub in fostering global research collaborations and sharing knowledge on wood waste biochar applications.

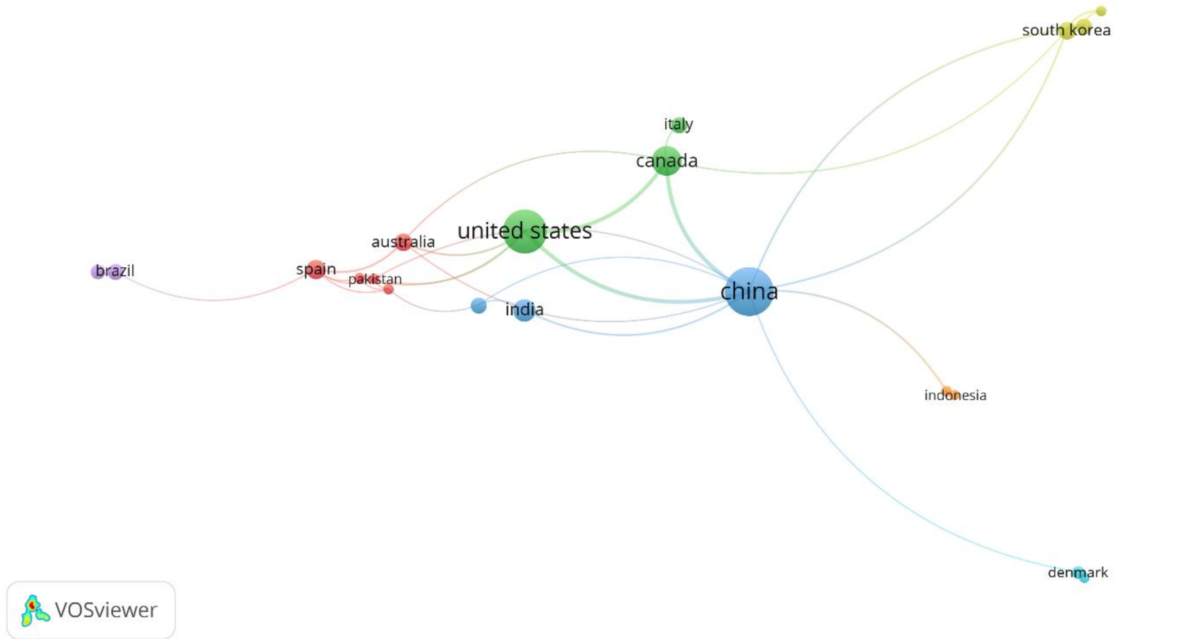
Table 1. Summary of research publications, citations, and collaboration link strength by country in the field of wood waste biochar as a biofertilizer

Country	Documents	Citations	Total Link Strength
China	37	2060	28
United States	31	2057	19
Canada	16	914	18
South Korea	7	956	8
Singapore	6	348	7
Australia	7	783	9
Spain	8	1177	6
Pakistan	3	199	5
Brazil	6	508	4
Czech Republic	3	54	4
Poland	3	56	4
Sri Lanka	3	165	4
Colombia	5	99	3
India	10	93	3
Sweden	3	52	3
United Kingdom	6	213	2
Denmark	4	52	2
Indonesia	3	55	2
Iran	2	128	1

China also stands out as a major hub, collaborating notably with Germany, Egypt, and India. The connections between China and these countries reflect the growing importance of Chinese research in the global context and its active role in forming research alliances. The link strength of China indicates a substantial level of collaboration, further emphasizing its significant contribution to the field. The United Kingdom is another key player in this network, forming notable links with countries including Switzerland and Poland. The UK's collaborative efforts highlight its role in advancing research through international partnerships. The connections between the UK and these countries suggest a strategic approach to leveraging diverse expertise and resources.

Other countries such as India, Brazil, and Germany also demonstrate considerable collaboration, forming a robust network of research partnerships. India shows notable links with countries like Egypt and Ghana, reflecting its active participation in international research networks. Brazil's collaborations with France and Mexico indicate its engagement in regional and global research efforts. Germany's connections with Spain and Egypt further highlight its role in fostering international research collaborations. Countries such as Spain, Australia, Singapore, South Korea, and Pakistan also play significant roles in this network. Spain, with its connections to the United States and Germany, shows strong involvement in the research community. Australia's links with countries like the United States and the United Kingdom indicate its active participation in global research efforts. Singapore's collaborations with China and Australia reflect its strategic positioning in the international research landscape. South Korea's links with the United States and Germany highlight its contributions to the field, while Pakistan's collaborations with China and the United Kingdom indicate its emerging role in this research domain.

Figure 3(b) illustrates the temporal overlay of the co-author network for countries involved in research on wood waste biochar as a biofertilizer, using colour coding to represent the timeline of collaborations. Darker shades indicate earlier collaborations, while lighter shades represent more recent ones, helping to understand the evolution of international research partnerships over time. The United States appears as a central node with collaborations spanning the entire timeline. The darker shades around its connections indicate that the United States has been a longstanding leader in fostering international research collaborations since the early 2010s, with ongoing and new partnerships up to the present. In contrast, China's node is predominantly shaded in lighter colours, suggesting that many of its international collaborations have formed more recently, particularly after 2015, reflecting a growing involvement in global research networks in recent years.
The United Kingdom shows a mix of darker and lighter shades, indicating a sustained and evolving network of collaborations over time, with both early and recent partnerships. India and Brazil exhibit a blend of colours; India shows more recent lighter shades, indicating an increase in its research collaborations in the past few years, while Brazil also shows a combination of early and recent collaborations, highlighting its continuous engagement in the research network. European countries like Germany, France, and Spain display nodes with a mix of shades, reflecting their active and sustained participation in international research collaborations over the years. The lighter shades indicate recent collaborations, suggesting ongoing research activity and partnerships. Countries such as South Korea, Australia, and Singapore have nodes with lighter shades, signifying that their international collaborations have primarily developed in recent years, highlighting the expanding global interest and involvement in the research on wood waste biochar as a biofertilizer. Overall, Figure 3(b) reveals a dynamic and evolving landscape of international research collaborations. While some countries have been long-term contributors to the field, others have increasingly joined the global research network more recently. This trend underscores the growing global recognition of the importance of wood waste biochar in sustainable agriculture and the value of international cooperation in advancing scientific knowledge and innovation in this area.



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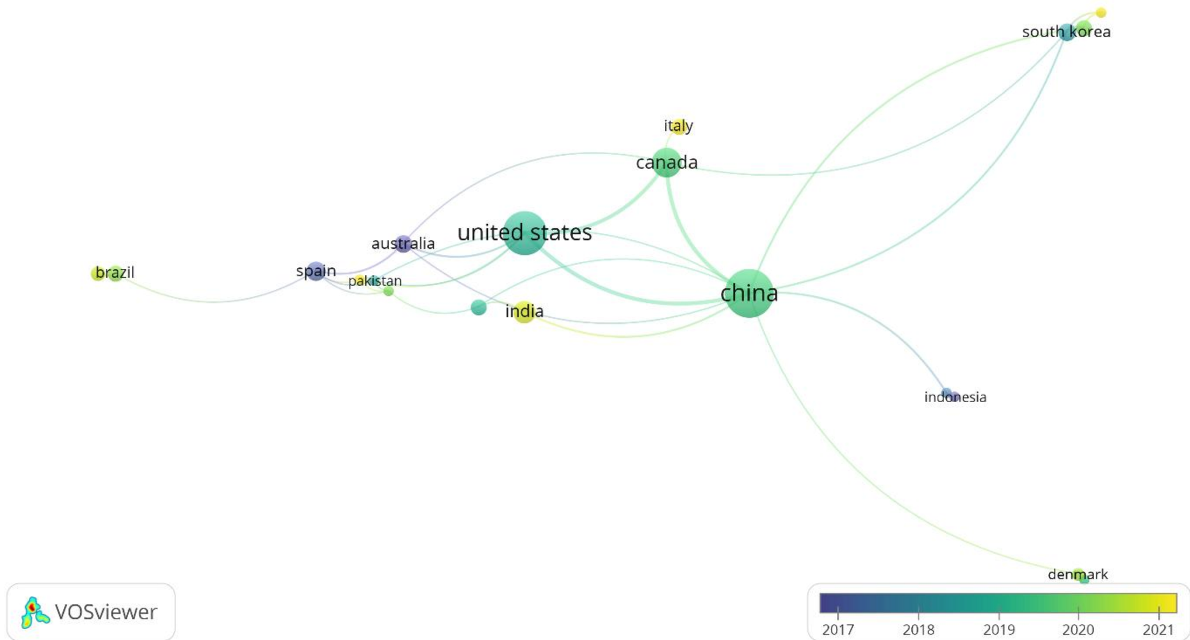

(b)

Figure 3. Illustration of the co-author network for countries, with a threshold set at 3, a total of 33 links and 7 clusters, within the domain of wood waste biochar to biofertilizer

3.3. Author Co-Citation Analysis in the Wood Waste Biochar to Biofertilizer

Table 2 provides a detailed summary of the most influential authors in the research domain of wood waste biochar as a biofertilizer. The table lists authors along with their respective number of citations and total link strength, which measures the degree of their collaborative impact within the research network. Lehmann J. stands out as the most influential author with 288 citations and an exceptional total link strength of 17,085, indicating a highly impactful and collaborative presence in the field. Gao B. follows with 128 citations and a total link strength of 11,679, highlighting significant contributions and strong collaborative networks. Ok Y.S. has 123 citations and a total link strength of 8,792, demonstrating considerable influence and extensive research collaborations. Li Y. and Joseph S. are also notable contributors, with Li Y. having 88 citations and a total link strength of 7,345, and Joseph S. having 119 citations and a total link strength of 7,218, reflecting their important roles in advancing research in this area.

Liu Y. (84 citations, 7,117 link strength) and Wang H. (86 citations, 7,017 link strength) both exhibit strong collaborative efforts and significant academic influence. Cao X. (71 citations, 6,859 link strength) and Chen H. (79 citations, 6,791 link strength) also play key roles, with substantial citations and collaboration networks. Wang Y. (81 citations, 6,300 link strength) and Zhang Y. (72 citations, 6,154 link strength) show strong research outputs and extensive collaborations. Zhang M. (69 citations, 6,030 link strength) and Chen B. (52 citations, 5,869 link strength) are influential figures with significant collaborative links. Mohan D. (71 citations, 5,760 link strength) and Zimmerman A.R. (66 citations, 5,689 link strength) contribute notably to the research community. Zhang Z. (57 citations, 5,521 link strength) and Wang S. (55 citations, 5,337 link strength) show strong collaboration and influence. Zhang X. (70 citations, 5,333 link strength) and Chen Y. (65 citations, 5,051 link strength) also demonstrate significant impact and collaborative efforts in the field. Overall, Table 2 highlights the leading authors in the research on wood waste biochar as a biofertilizer, emphasizing their contributions through citations and collaborative link strength. These metrics underscore the importance of their work and their influence within the scientific community.

Table 2. Summarization of the number of citations and total link strength for each author involved in the research on wood waste biochar to biofertilizer

Author	Citations	Total Link Strength
Lehmann J.	288	17085
Gao B.	128	11679
Ok Y.S.	123	8792
Li Y.	88	7345
Joseph S.	119	7218
Liu Y.	84	7117

Author	Citations	Total Link Strength
Wang H.	86	7017
Cao X.	71	6859
Chen H.	79	6791
Wang Y.	81	6300
Zhang Y.	72	6154
Zhang M.	69	6030
Chen B.	52	5869
Mohan D.	71	5760
Zimmerman A.R.	66	5689
Zhang Z.	57	5521
Wang S.	55	5337
Zhang X.	70	5333
Chen Y.	65	5051

Figure 4 presents the co-citation network for cited authors within the domain of wood waste biochar to biofertilizer, with a threshold set at 20 citations. This results in a network with 12,870 links and four distinct clusters. Each node represents an author, with the size of the node reflecting the number of citations received. The links between nodes indicate co-citation relationships, with thicker lines representing stronger or more frequent co-citations. The clusters are color-coded to represent different groups of closely related authors based on their co-citation patterns.

The green cluster is centred around Lehmann J., one of the most influential authors in the field, as indicated by the large size of his node. This cluster includes authors such as Joseph S., Steiner C., Glaser B., and Chan K.Y., indicating a strong interconnected group that significantly contributes to the research on biochar. The green cluster represents a foundational group with extensive collaborations and co-citations, emphasizing their pivotal role in advancing the understanding and application of wood waste biochar in sustainable agriculture. The red cluster includes authors such as Wang H., Li Y., Liu Y., and Zhang Y. This cluster shows a dense network of co-citations, indicating a tightly knit research community that frequently cites each other's work. The presence of multiple authors from China suggests that this cluster may focus on specific regional studies or methodologies prevalent in Chinese research on biochar.

The blue cluster is centred around Gao B., Ok Y.S., and Zimmerman A.R. This cluster represents another core group of researchers with significant contributions to the field. The connections within this cluster highlight extensive collaborations and mutual citations, suggesting that these authors have made substantial contributions to specific aspects or applications of wood waste biochar. The yellow cluster includes authors such as Chen H., Zhang Z., and Wang Q. This group, while smaller, still shows a strong interconnected network of co-citations. The presence of this cluster indicates additional thematic or methodological areas within the broader research domain, contributing diverse perspectives and findings to the study of biochar.

The overall network shows a high degree of interconnectivity, with numerous links between authors across different clusters. This interconnectedness reflects the collaborative nature of research in the field of wood waste biochar as a biofertilizer, highlighting the importance of shared knowledge and co-authorship in advancing scientific understanding. The presence of 12,870 links indicates a robust and dynamic research community, where influential authors frequently cite each other's work, fostering a cumulative and integrative approach to knowledge building.

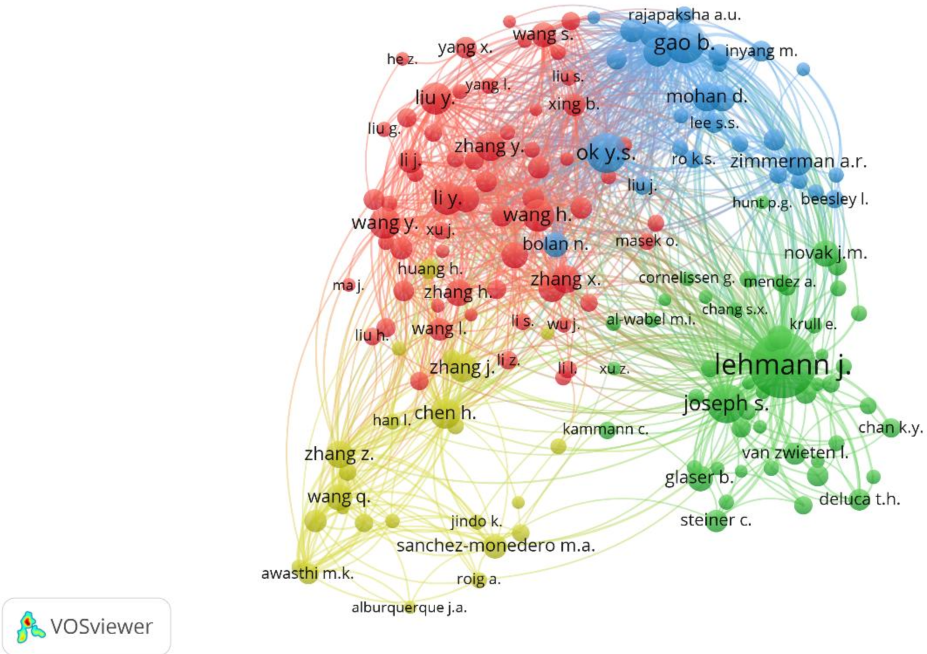

Figure 4. Illustration of the co-citation network for cited authors, with a threshold set at 20, a total of 12870 links and 4 cluster, within the domain of wood waste biochar to biofertilizer.

3.4. Co-Citation of Journals in the Wood Waste Biochar to Biofertilizer

Table 3 provides a detailed overview of the most influential journals in the research field of wood waste biochar as a biofertilizer. Bioresource Technology emerges as the most influential journal with 377 citations and a total link strength of 11,970, indicating its pivotal role in disseminating key research findings and fostering significant scholarly connections. Chemosphere follows with 277 citations and a total link strength of 9,536, highlighting its substantial contribution to the field and its extensive network of citations. Science of the Total Environment has 177 citations and a total link strength of 7,903, reflecting its importance in covering comprehensive environmental research, including studies on biochar.

Table 3. Summarization of the number of citations and total link strength for each sources involved in the research on wood waste biochar to biofertilizer

Source	Citations	Total Link Strength
Bioresource Technology	377	11970
Chemosphere	277	9536
Science of the Total Environment	177	7903
Environmental Science & Technology	145	4673
Journal of Hazardous Materials	83	3780
Environmental Pollution	73	3427
Environmental Science & Technology	42	2731
Biomass and Bioenergy	90	2692
Soil Biology and Biochemistry	79	2585
Fuel	67	2564
Chemical Engineering Journal	65	2536
Journal of Cleaner Production	65	2401
Geoderma	76	2259
Water Research	55	2063
Journal of Analytical & Applied Pyrolysis	55	1884
Journal of Environmental Management	53	1831

Environmental Science & Technology is notable with 145 citations and a total link strength of 4,673, emphasizing its impact on technological advancements in environmental science. The Journal of Hazardous Materials, with 83 citations and a total link strength of 3,780, plays a significant role in addressing the risks and management of hazardous materials, including biochar applications. Environmental Pollution and Environmental Science & Technology have 73 and 42 citations respectively, with total link strengths of 3,427 and 2,731, indicating their influence in pollution studies and environmental technology.

Biomass and Bioenergy (90 citations, 2,692 link strength) and Soil Biology and Biochemistry (79 citations, 2,585 link strength) are key sources for biochar research, particularly in bioenergy and soil science. Fuel (67 citations, 2,564 link strength) and Chemical Engineering Journal (65 citations, 2,536 link strength) contribute significantly to the engineering and chemical aspects of biochar production and utilization. The Journal of Cleaner Production, with 65 citations and a total link strength of 2,401, highlights the focus on sustainable and cleaner production methods involving biochar.

Geoderma (76 citations, 2,259 link strength) and Water Research (55 citations, 2,063 link strength) indicate strong contributions in soil science and water research related to biochar. The Journal of Analytical and Applied Pyrolysis and the Journal of Environmental Management have 55 and 53 citations respectively, with total link strengths of 1,884 and 1,831, highlighting their roles in pyrolysis processes and environmental management. Overall, Table 3 highlights the leading journals in the field of wood waste biochar as a biofertilizer, emphasizing their contributions through citations and collaborative link strengths. These metrics underscore the significance of these journals in advancing research and fostering collaborations within the scientific community.

Figure 5 presents the co-citation network for cited sources within the domain of wood waste biochar to biofertilizer, with a threshold set at 20 citations. The network consists of 1,284 links and is divided into four distinct clusters, each represented by different colours. Each node in the network represents a journal, with the size of the node indicating the number of citations. The links between nodes represent co-citation relationships, with thicker lines indicating stronger or more frequent co-citations. The red cluster is centred around Chemosphere, one of the most frequently co-cited journals in this field. This cluster includes significant journals such as Biomass and Bioenergy, Plant and Soil, and Soil Biology and Biochemistry, focusing on environmental and soil science aspects of biochar research. This highlights the interconnectedness of studies related to soil health, pollution, and bioenergy.

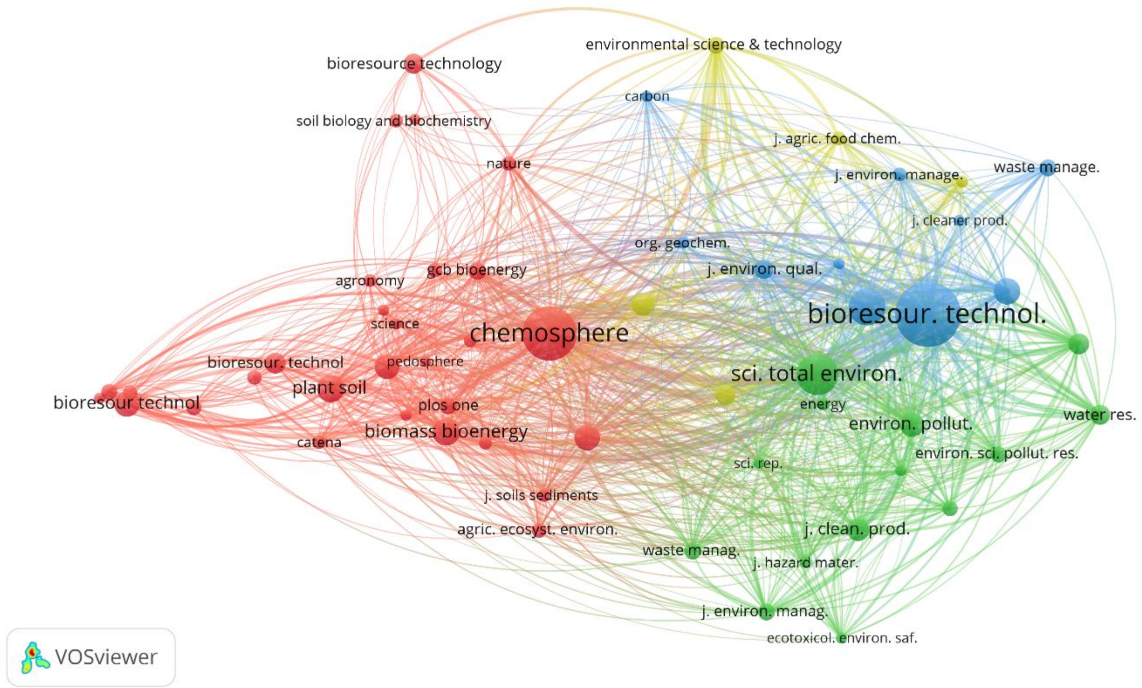

Figure 5. Illustration of the co-citation network for cited sources, with a threshold set at 20, a total of 1284 links and 4 clusters, within the domain of wood waste biochar to biofertilizer

The green cluster is centred around Bioresource Technology, another highly influential journal in this domain. It includes journals such as Science of the Total Environment, Environmental Pollution, and Journal of Cleaner Production, representing research on biochar production, environmental impacts, and sustainable technologies. This cluster emphasizes the broad applications and interdisciplinary nature of biochar research. The blue cluster includes key journals like Environmental Science & Technology, Water Research, and Journal of Hazardous Materials. This cluster focuses on the technological and environmental engineering aspects of biochar, including waste management, water treatment, and hazardous material management. The strong co-citation links within this cluster indicate robust collaborations and shared knowledge among these journals.

The yellow cluster includes journals such as Journal of Environmental Management and Journal of Agricultural and Food Chemistry. This smaller cluster likely represents specialized areas within biochar research, including agricultural applications and environmental management practices. The co-citation patterns in this cluster highlight specific research themes related to biochar's role in agriculture and food safety. Overall, Figure 5 shows a high degree of interconnectivity, with numerous links between journals across different clusters, reflecting the collaborative nature of research in the field of wood waste biochar as a biofertilizer. The presence of 1,284 links indicates a robust and dynamic research community, where influential journals frequently cite each other's work, fostering a cumulative and integrative approach to knowledge building. The four clusters provide a clear visualization of the main research groups and their interrelations, highlighting key journals and their collaborative networks. This analysis underscores the significance of co-citation as a measure of research influence and collaboration, demonstrating how collective efforts drive innovation and progress in sustainable agriculture practices.

3.5. Co-Occurrence of authors' Keywords in the Wood Waste Biochar to Biofertilizer

Table 4 provides a detailed overview of the most frequently occurring keywords in the research field of wood waste biochar as a biofertilizer, listing each keyword along with its occurrences and total link strength. The keyword Biochar stands out with 74 occurrences and a total link strength of 72, highlighting its central role in this research area. Pyrolysis, with 22 occurrences and a total link strength of 26, is crucial as it relates to the process of biochar production. Biomass appears 8 times with a total link strength of 15, underscoring its importance as a raw material for biochar. Adsorption is noted 11 times with a link strength of 12, reflecting its significance in the applications of biochar. Compost and Composting appear 6 and 5 times respectively, with link strengths of 9 and 8, indicating their roles in integrated waste management practices. Sustainable Agriculture occurs 7 times with a link strength of 8, emphasizing the relevance of biochar in promoting sustainable farming practices.

Table 4 Keyword Occurrences and Total Link Strength in Research on Wood Waste Biochar to Biofertilizer

Keyword	Occurrences	Total Link Strength
Biochar	74	72
Pyrolysis	22	26
Biomass	8	15
Adsorption	11	12
Compost	6	9
Composting	5	8
Sustainable Agriculture	7	8
Heavy Metals	3	7
Pig Manure	5	7

Keyword	Occurrences	Total Link Strength
Slow Pyrolysis	4	7
Soil Amendment	6	6
Biosolids	4	6
Manure	3	5
Sorption	4	6
Nitrogen	3	5
Potassium	3	4
Wood Ash	3	4
Co-pyrolysis	3	3
Nutrient Availability	3	3

Keywords such as Heavy Metals and Pig Manure each have 3 and 5 occurrences respectively, with a link strength of 7, highlighting research on biochar's role in contaminant management and nutrient cycling. Slow Pyrolysis appears 4 times with a link strength of 7, indicating a specific focus within the broader pyrolysis category. Soil Amendment, with 6 occurrences and a link strength of 6, underscores its importance in improving soil health using biochar. Additional keywords such as Biosolids, Sorption, and Manure have occurrences ranging from 3 to 4, with link strengths of 6 and 5, reflecting their relevance in biochar research. Nitrogen, Potassium, and Wood Ash each have 3 occurrences, with link strengths of 5 and 4, indicating their role in studies related to nutrient management. Co-pyrolysis and Nutrient Availability each have 3 occurrences and a link strength of 3, highlighting emerging areas of interest within the biochar research community. Overall, Table 4 illustrates the key themes and research areas in the study of wood waste biochar as a biofertilizer, providing insights into the most relevant topics and their interconnectedness within the research community.

Figure 6 illustrates the co-occurrence network of authors' keywords in the research domain of wood waste biochar as a biofertilizer, with a minimum keyword threshold of 3 and a total of 57 links, organized into 6 distinct clusters. Each node represents a keyword, and the size of the node indicates the frequency of its occurrence. The links between nodes represent co-occurrence relationships, with thicker lines indicating stronger or more frequent co-occurrences. The red cluster is centred around the keyword Biochar, which is the most frequently occurring keyword, indicating its fundamental importance in this research field. This cluster also includes keywords such as Compost, Nutrient Availability, Organic Waste, and Sorption. These keywords highlight research themes related to soil health, nutrient management, and waste utilization. The focus of this cluster is on integrating biochar with compost and other organic amendments to enhance soil fertility and manage waste. The strong connections among these keywords suggest a significant amount of research exploring the synergistic effects of combining biochar with other organic materials to improve soil quality and nutrient retention.

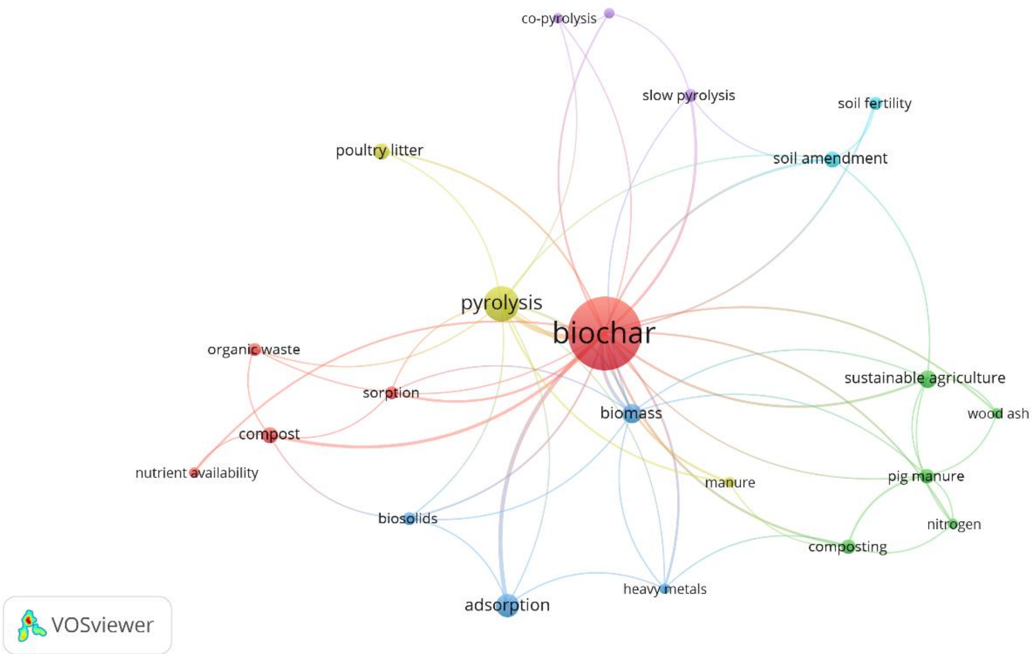

Figure 6. Co-occurrence of authors' keywords: Minimum keywords threshold of 3 and 57 link with 6 cluster

The green cluster includes keywords like Sustainable Agriculture, Pig Manure, Nitrogen, and Composting, focusing on agricultural applications of biochar. This cluster reflects the interest in using biochar to improve soil fertility, recycle agricultural waste, and promote sustainable farming practices. The presence of these keywords indicates that researchers are actively investigating how biochar can be used to enhance the sustainability of agricultural systems. This includes its role in nutrient cycling, improving soil structure, and reducing greenhouse gas emissions from agricultural activities.

The blue cluster emphasizes environmental applications of biochar, featuring keywords such as Adsorption, Biosolids, Heavy Metals, and Biomass. The keywords in this cluster indicate research on using biochar for the adsorption of contaminants, managing biosolids, and utilizing biomass as a feedstock for biochar production. The focus here is on biochar's capacity to immobilize heavy metals and other pollutants, making it a valuable tool for environmental remediation. Additionally, this cluster highlights the importance of using various biomass sources for biochar production, which can influence the properties and effectiveness of the resulting biochar.

The yellow cluster contains keywords like Pyrolysis, Co-pyrolysis, and Slow Pyrolysis, focusing on the technological processes involved in biochar production. The presence of multiple pyrolysis-related keywords highlights the significance of these methods in determining biochar properties and effectiveness. Research in this cluster is dedicated to optimizing pyrolysis conditions, exploring different pyrolysis techniques, and understanding how these processes affect the physical and chemical characteristics of biochar. This cluster underscores the importance of production technology in enhancing the quality and functionality of biochar.

The purple cluster includes keywords like Soil Amendment and Soil Fertility, reflecting the application of biochar in improving soil health. This cluster underscores the role of biochar as a soil amendment to enhance soil structure, fertility, and overall productivity. Research in this area focuses on how biochar can improve soil water retention, increase nutrient availability, and support healthy microbial communities. The connections within this cluster suggest ongoing studies on the benefits of biochar for various types of soils and crops, aiming to optimize its use for agricultural purposes.

The aqua cluster comprises the keyword Poultry Litter, pointing to specific feedstocks used in biochar production. Research in this cluster explores the unique properties and applications of biochar derived from poultry litter and its impact on soil and crop performance. The focus here is on understanding how different feedstocks influence the characteristics of biochar and how these variations affect its efficacy as a soil amendment. This cluster highlights the importance of feedstock selection in biochar production and its implications for agricultural and environmental applications.

Overall, Figure 6 provides a detailed visualization of the key themes, emerging trends, and research dynamics in the field of wood waste biochar as a biofertilizer. It highlights both established and emerging areas of interest, illustrating the interconnected and evolving nature of this multidisciplinary research area. The analysis of these clusters reveals the diverse applications and benefits of biochar, from improving soil health and agricultural sustainability to environmental remediation and waste management.

Figure 7 and Table 5 illustrate the overlay co-occurrence network of authors' keywords in the research domain of wood waste biochar to biofertilizer, highlighting the temporal evolution of research activity from 2017 to 2022. Each node represents a keyword, with the size of the node indicating the frequency of its occurrence. The links between nodes represent co-occurrence relationships, with thicker lines indicating stronger or more frequent co-occurrences. The colour gradient from blue to yellow reflects the timeline, with blue indicating earlier years (2017) and yellow indicating more recent years (2022).

Biochar is the central keyword, reflecting its fundamental importance in the research domain. It connects with various themes such as soil health, environmental applications, and pyrolysis techniques. Pyrolysis frequently co-occurs with biochar, indicating the importance of the production process. This keyword has been consistently relevant throughout the period. Biomass, a key raw material for biochar production, shows significant connections with biochar, pyrolysis, and other related themes. Adsorption highlights biochar's capacity to capture contaminants and is frequently linked with environmental applications and soil remediation.

Emerging and evolving keywords include Sustainable Agriculture, which reflects the increasing interest in using biochar for sustainable farming practices. The lighter colour indicates more recent research activity, particularly from 2020 to 2022. Keywords like Pig Manure and Wood Ash, which represent specific feedstocks for biochar production, show more recent research focus, emerging prominently in the last few years. Slow Pyrolysis and Co-pyrolysis, which indicate specific pyrolysis techniques, have gained attention in recent years, as shown by the yellowish colour of their nodes.

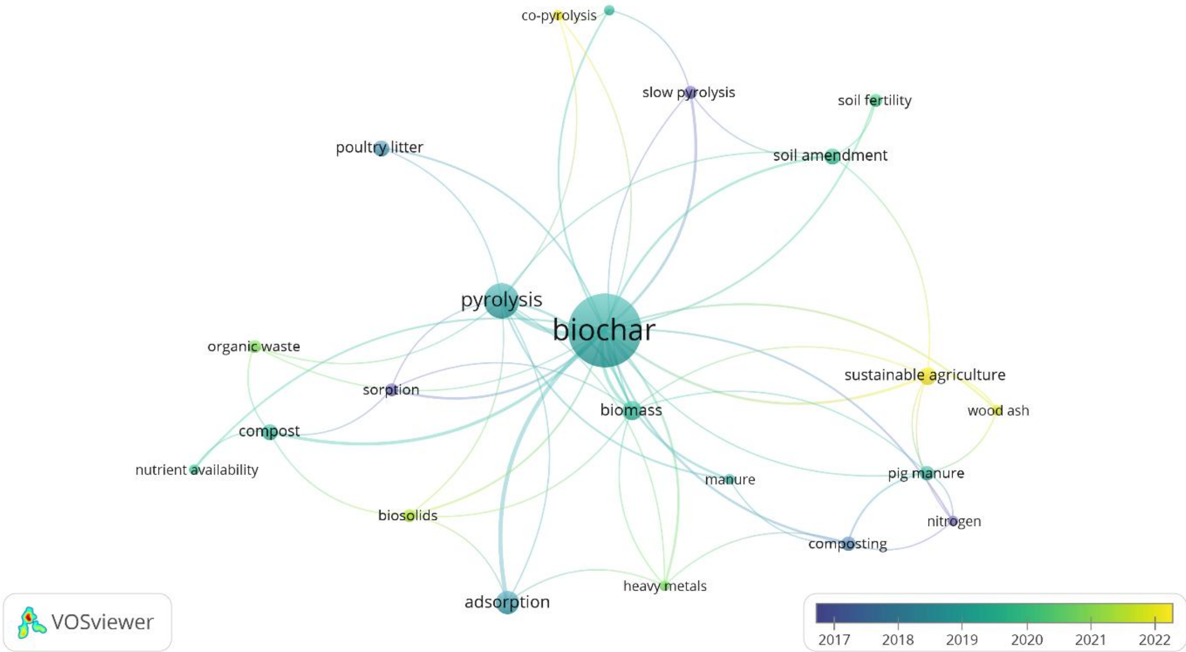

Figure 7. Overlay co-occurrence of authors' keywords on wood waste biochar to biofertilizer

Consistent research themes are represented by keywords such as Soil Amendment and Soil Fertility, which are consistently associated with biochar, highlighting its role in improving soil quality and fertility. These terms have been relevant throughout the analysed period. Composting and Compost reflect the integration of biochar with composting practices, related to soil health and nutrient management, and have shown steady research interest. Heavy Metals and Biosolids indicate environmental applications of biochar, focusing on contaminant immobilization and waste management, maintaining their importance over the years.

The colour gradient in Figure 7 provides insights into the evolution of research topics over time. From 2017 to 2018 (blue), earlier research focused on foundational aspects of biochar, such as its production through pyrolysis, and its basic applications in soil amendment and adsorption. From 2019 to 2020 (green), research expanded to explore specific applications and feedstocks, including the use of pig manure and the development of slow pyrolysis techniques. From 2021 to 2022 (yellow), recent studies have emphasized sustainable agriculture and advanced pyrolysis methods like co-pyrolysis, with increased interest in these areas in the latest years.

Table 5. Overlay co-occurrence of authors' keywords on wood waste biochar to biofertilizer (Figure 7)

Keyword	Year	Explanation
Biochar	2017-2021	Central keyword indicating the primary focus of the research. Linked with various themes such as soil health, environmental applications, and pyrolysis techniques.

Keyword	Year	Explanation
Pyrolysis	2017-2021	Important keyword associated with the production process of biochar. Frequently co-occurs with keywords related to technological processes.
Biomass	2017-2021	Key raw material for biochar production. Co-occurs with keywords related to feedstocks and environmental benefits.
Adsorption	2017-2021	Highlights biochar's capacity to capture contaminants. Often linked with environmental applications and soil remediation.
Compost	2017-2021	Represents the integration of biochar with composting practices. Related to soil health and nutrient management.
Composting	2017-2021	Indicates the use of biochar in composting processes. Focuses on waste management and soil improvement.
Sustainable Agriculture	2017-2021	Reflects the use of biochar in sustainable farming practices. Linked with soil fertility and nutrient cycling.
Heavy Metals	2017-2021	Associated with research on biochar's ability to immobilize contaminants. Highlights its environmental remediation potential.
Pig Manure	2019-2021	Specific feedstock used in biochar production. Linked with studies on nutrient recycling and soil amendment.
Slow Pyrolysis	2019-2021	Specific pyrolysis technique used for biochar production. Related to optimizing biochar properties and performance.
Soil Amendment	2017-2021	Highlights the use of biochar to improve soil quality. Connected with themes of soil fertility and crop productivity.
Biosolids	2017-2021	Indicates the use of biosolids as a feedstock for biochar. Related to waste management and soil improvement.
Manure	2017-2021	General term related to various types of manure used as biochar feedstock. Focuses on nutrient cycling and soil health.
Sorption	2017-2021	Represents biochar's ability to absorb or adsorb substances. Linked with studies on contaminant capture and nutrient retention.
Nitrogen	2017-2021	Reflects research on biochar's effect on nitrogen cycles in soil. Connected with soil fertility and crop productivity.
Potassium	2017-2021	Indicates biochar's role in enhancing soil potassium levels. Related to soil fertility and nutrient management.
Wood Ash	2019-2021	Specific feedstock and byproduct of biochar production. Linked with studies on soil amendment and nutrient content.
Co-pyrolysis	2019-2021	Technique involving the pyrolysis of multiple feedstocks. Focuses on optimizing biochar characteristics and performance.
Nutrient Availability	2017-2021	Highlights biochar's impact on soil nutrient availability. Related to themes of soil fertility and sustainable agriculture.

3.6 Network View Map Based on Abstract and Title for Wood Waste Biochar to Biofertilizer Applications Generated by the VOS viewer

Table 6 presents the overlay co-occurrence of authors' keywords, highlighting the frequency (occurrences) and importance (relevance) of specific terms within the abstracts and titles of research publications related to wood waste biochar applications for biofertilizers. Ammonium appears 14 times with a high relevance score of 6.50, indicating its significant role in nutrient dynamics in soil. Phosphate occurs 18 times with a relevance score of 5.56, reflecting its importance in nutrient management and soil fertility enhancement using biochar. Urine, found 19 times with a relevance score of 4.42, suggests research interest in utilizing urine as a nutrient source in biochar applications. Wood Waste occurs 17 times with a relevance score of 2.57, highlighting the utilization of wood waste as a feedstock for biochar production.

Industrial Waste appears 10 times with a relevance score of 2.29, indicating research on using industrial waste for biochar production and its environmental implications. GHG Emission, found 12 times with a relevance score of 2.27, reflects studies on biochar's impact on greenhouse gas emissions. Food Waste occurs 12 times with a relevance score of 2.02, showing interest in converting food waste into biochar for sustainable waste management. Removal appears 29 times with a relevance score of 1.73, indicating a focus on biochar's ability to remove contaminants from soil and water. Wood Charcoal, found 11 times with a relevance score of 1.57, relates to studies on the properties and uses of wood-derived biochar. NH3 occurs 10 times with a relevance score of 1.51, related to ammonia dynamics in soil treated with biochar. BCW appears 10 times with a relevance score of 1.48, likely referring to biochar water content or a specific study acronym.

Bio Oil, found 15 times with a relevance score of 1.34, indicates interest in bio-oil co-products from pyrolysis processes. Raw Material occurs 19 times with a relevance score of 1.33, highlighting the various raw materials used for biochar production. Potassium appears 18 times with a relevance score of 1.21, reflecting the role of biochar in enhancing soil potassium levels. Day, found 21 times with a relevance score of 1.16, possibly relates to the duration of experiments or effects observed over time. Immobilization Effect occurs 12 times with a relevance score of 1.13, indicating studies on biochar's ability to immobilize contaminants in soil.

Co-Pyrolysis, appearing 14 times with a relevance score of 1.09, shows interest in the process of pyrolyzing multiple feedstocks together. CO2, found 14 times with a relevance score of 1.06, reflects studies on carbon dioxide emissions and sequestration related to biochar. Poultry occurs 31 times with a relevance score of 1.06, indicating research on using poultry waste as a feedstock for biochar production. This table provides a comprehensive overview of the key terms and their significance in the research literature on wood waste biochar applications for biofertilizers, highlighting the main themes and areas of focus within this multidisciplinary field.

Table 6 Overlay Co-Occurrence of Authors' Keywords based on Abstract and Title

Term	Occurrences	Relevance
Ammonium	14	6.50
Phosphate	18	5.56
Urine	19	4.42
Wood Waste	17	2.57
Industrial Waste	10	2.29

Term	Occurrences	Relevance
GHG Emission	12	2.27
Food Waste	12	2.02
Removal	29	1.73
Wood Charcoal	11	1.57
NH3	10	1.51
BCW	10	1.48
Bio Oil	15	1.34
Raw Material	19	1.33
Potassium	18	1.21
Day	21	1.16
Immobilization Effect	12	1.13
Co-Pyrolysis	14	1.09
CO2	14	1.06
Poultry	31	1.06

Figure 8 presents a network view map generated by VOS viewer, based on the abstracts and titles of research publications related to wood waste biochar applications for biofertilizers. This map visualizes the co-occurrence of terms with a minimum threshold of 10 occurrences, resulting in a network of 1263 links and 5 distinct clusters. The blue cluster is prominently positioned and includes terms such as treatment, compost, addition, and composting. This cluster focuses on the integration of biochar into composting processes and its role in soil treatment and amendment. The strong connections among these terms highlight the importance of biochar in enhancing compost quality and its effectiveness as a soil additive.

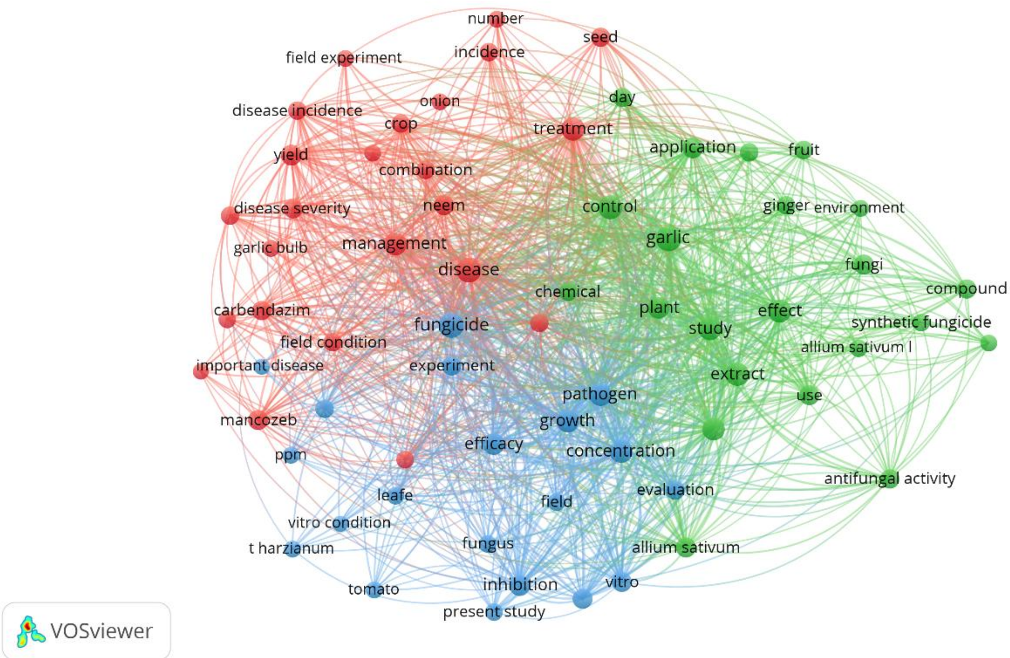

Figure 8. Network view map based on abstract and title generated by VOS viewer with minimum occurrences of 10, 1263 links, and 5 clusters

The red cluster centres around keywords like feedstock, pyrolysis, soil amendment, and biochar yield. This cluster emphasizes the production aspects of biochar, particularly the use of various feedstocks and the optimization of pyrolysis conditions to maximize biochar yield. The terms industrial waste and co-pyrolysis indicate the exploration of diverse raw materials and pyrolysis techniques. The green cluster includes terms such as production, temperature, impact, and review. This cluster is associated with the scientific evaluation and optimization of biochar production processes, highlighting research on the effects of different production parameters, such as temperature, on biochar quality and performance.

The yellow cluster features keywords like phosphate, wood waste, removal, and adsorption. This cluster focuses on the environmental applications of biochar, particularly its ability to adsorb contaminants and nutrients like phosphate from waste streams. The terms wood waste and potassium suggest an emphasis on the valorisation of wood residues and the nutrient content of biochar. The purple cluster includes terms such as experiment, term, medium, and amendment. This cluster represents a more general focus on experimental research and methodological aspects related to biochar applications. It highlights the various experimental setups and research methodologies used to study biochar's effectiveness as a soil amendment.

Figure 9 and Table 7 illustrate the overlay co-occurrence network of terms found in the abstracts and titles of research publications related to wood waste biochar to biofertilizer applications, generated using VOS viewer. This map visualizes the temporal evolution of research activity from 2018 to 2021, with each node representing a term and the size of the node indicating the frequency of its occurrence. The links between nodes represent co-occurrence relationships, with thicker lines indicating stronger or more frequent co-occurrences. The colour gradient from blue to yellow reflects the timeline, with blue indicating earlier years (2018) and yellow indicating more recent years (2021).

In 2018, the focus was primarily on foundational aspects and general applications of biochar. Prominent terms during this period included "phosphate" and "wood waste," indicating an emphasis on nutrient management and the utilization of wood waste as a feedstock for biochar production. Terms like "adsorption" and "removal" highlighted initial studies on biochar’s environmental applications, particularly its ability to capture and remove contaminants.

By 2019, research began to delve deeper into the production processes and specific feedstocks for biochar. Keywords such as "pyrolysis," "feedstock," and "industrial waste" gained prominence, reflecting an interest in optimizing biochar production techniques and exploring diverse raw materials. The term "temperature" indicated studies on how different pyrolysis conditions affect biochar properties. "Potassium" also emerged as a significant term, highlighting research on biochar’s role in enhancing soil nutrient levels.

In 2020, the focus expanded to include the practical applications of biochar in soil treatment and composting. Terms like "treatment," "compost," and "composting" became more prominent, indicating increased research on integrating biochar into composting processes and its effectiveness as a soil additive. "Production" and "impact" continued to be significant, with studies evaluating the overall effectiveness of biochar applications. "GHG emission" also appeared, reflecting interest in biochar's potential to mitigate greenhouse gas emissions.

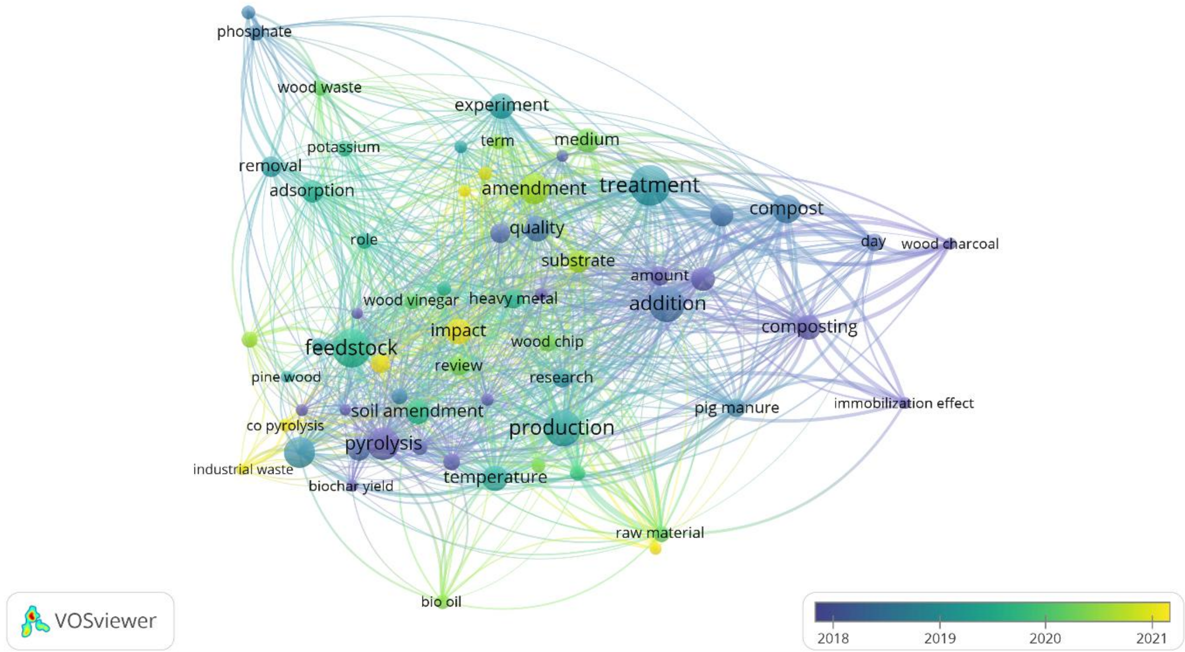

Figure 9. Overlay co-occurrence of authors' abstract and title for wood waste biochar to biofertilizer applications

The most recent research in 2021 highlights emerging areas of focus and new applications for biochar. Keywords such as "addition," "immobilization effect," and "co-pyrolysis" indicate innovative approaches and techniques being explored. "Pig manure" and "raw material" suggest ongoing interest in using various agricultural and industrial wastes as feedstocks. "Biochar yield" and "bio-oil" reflect efforts to optimize the production process and explore valuable co-products of pyrolysis. Additionally, "amendment" and "quality" highlight a continuous interest in enhancing soil quality through biochar applications.

Overall, Figure 9 provides a comprehensive overview of the temporal trends in the research on wood waste biochar applications for biofertilizers. It shows how the focus has evolved from foundational studies on nutrient management and feedstock utilization to more specific applications and optimization of production processes. The temporal overlay effectively illustrates how research priorities have shifted over the years, providing valuable insights into the dynamic and evolving nature of this multidisciplinary field.

Table 7. Summary of key clusters, keywords, descriptions, and years from figure 9

Cluster	Key Keywords	Description	Years
Blue	Treatment, Compost, Addition, Composting, Day	Research focus on integrating biochar into composting processes	2020-2021

Cluster	Key Keywords	Description	Years
		and its role in soil treatment and amendment.	
Red	Feedstock, Pyrolysis, Soil Amendment, Biochar Yield, Industrial Waste, Co-pyrolysis, Bio Oil	Emphasis on the production aspects of biochar, particularly the use of various feedstocks and optimization of pyrolysis conditions.	2018-2020
Green	Production, Temperature, Impact, Review	Scientific evaluation and optimization of biochar production processes, highlighting research on production parameters and their effects.	2019-2021
Yellow	Phosphate, Wood Waste, Removal, Adsorption, Potassium	Focus on biochar's ability to adsorb contaminants and nutrients from waste streams, emphasizing environmental applications and nutrient management.	2018-2020
Purple	Experiment, Term, Medium	General focus on experimental research and methodological aspects related to biochar applications, covering various experimental setups and methodologies.	2018-2021

4. Deep Analysis of the Top Cited Documents in Wood Waste Biochar to Biofertilizer Applications

Section 4 provides a comprehensive examination of the most highly cited documents in the field of wood waste biochar to biofertilizer applications. This analysis aims to highlight the significant contributions and pivotal research that have shaped the current understanding and advancements in this domain. By focusing on the top-cited works, this section seeks to identify key themes, methodologies, and findings that have driven the development and application of biochar derived from wood waste in enhancing soil fertility and environmental sustainability. These influential studies offer valuable insights into the effectiveness, challenges, and future directions of using biochar as a biofertilizer, providing a foundation for ongoing and future research efforts.

Table 8 presents a selection of the most influential and highly cited documents in the field of wood waste biochar applications for biofertilizers, highlighting the breadth of research and key contributions that have significantly impacted this area of study. The seminal work by Lee et al. (2013), titled "Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C" and published in Bioresource Technology, investigates the properties of biochar derived from various biomass residues through slow pyrolysis at 500°C. With 472 citations, this study provides a comparative analysis of the physical and chemical characteristics of biochar, crucial for understanding its suitability and effectiveness in soil amendment and environmental applications.

Domingues et al. (2017) in PLoS ONE, with 409 citations, explores the properties of biochar produced from wood and other high-nutrient biomasses, emphasizing its agronomic and environmental benefits and its potential to enhance soil fertility. Xie et al. (2015) provide a comprehensive review in Critical Reviews in Environmental Science and Technology, synthesizing existing knowledge on biochar and identifying key areas for its application in addressing environmental challenges such as soil contamination and water purification, with 385 citations.

Hassan et al. (2020) in Science of the Total Environment, with 349 citations, present a meta-analysis examining how different feedstock sources and pyrolysis temperatures influence the properties of biochar and its functionality as an adsorbent, providing valuable insights for optimizing biochar production. Alburquerque et al. (2013) in Agronomy for Sustainable Development investigate the effects of biochar addition on wheat yield under various mineral fertilization regimes, demonstrating biochar's potential to improve crop productivity in sustainable agriculture, with 260 citations.

Rosales et al. (2017) in Bioresource Technology review challenges and recent advances in using biochar as a low-cost biosorbent, covering both batch assays and continuous-flow systems, with 201 citations. Lonappan et al. (2016) in Waste Management focus on the adsorption capabilities of biochar microparticles derived from different waste materials, specifically targeting the removal of methylene blue from aqueous solutions, also with 201 citations.

Xu et al. (2018) in Journal of Cleaner Production explore the recovery of ammonium and phosphate from urine as value-added fertilizer using wood waste biochar loaded with magnesium oxides, addressing waste management while producing valuable fertilizers, with 199 citations. Akdeniz (2019) in Waste Management provides a systematic review of biochar use in animal waste composting, highlighting its role in enhancing compost quality and reducing greenhouse gas emissions, with 174 citations. Wang et al. (2020) in Science of the Total Environment investigate the adsorption mechanisms of biochar for heavy metals like Ni (II), Cu (II), and Cd (II), emphasizing the influence of feedstock type and providing critical insights for environmental remediation, with 168 citations. This detailed description of Table 8 highlights the significant contributions of each study, providing a comprehensive overview of the top-cited documents in the field of wood waste biochar to biofertilizer applications.

Table 8. Top cited documents on wood waste biochar to biofertilizer applications

Authors	Title	Year	Source Title	Cited by	Description	Ref.
Lee Y.; Park J.; Ryu C.; Gang K.S.; Yang W.; Park Y.-K.; Jung J.; Hyun S.	Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C	2013	Bioresource Technology	472	This seminal work by Lee et al. investigates the properties of biochar derived from various biomass residues through slow pyrolysis at 500°C.	[32]
Domingues R.R.; Trugilho P.F.; Silva C.A.; De Melo I.C.N.A.; Melo L.C.A.; Magriotis Z.M.; Sánchez-Monedero M.A.	Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits	2017	PLoS ONE	409	Domingues et al. explore the properties of biochar produced from wood and other high-nutrient biomasses.	[33]
Xie T.; Reddy K.R.; Wang C.; Yargicoglu E.; Spokas K.	Characteristics and applications of biochar for environmental remediation: A review	2015	Critical Reviews in Environmental Science and Technology	385	Xie et al. provide a comprehensive review of biochar characteristics and its applications in environmental remediation.	[34]
Hassan M.; Liu Y.; Naidu R.; Parikh S.J.; Du J.; Qi F.; Willett I.R.	Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis	2020	Science of the Total Environment	349	This meta-analysis by Hassan et al. examines how different feedstock sources and pyrolysis temperatures influence the properties of biochar and its functionality as an adsorbent.	[35]
Alburquerque J.A.; Salazar P.; Barrón V.; Torrent J.; Del Campillo M.D.C.; Gallardo A.; Villar R.	Enhanced wheat yield by biochar addition under different mineral fertilization levels	2013	Agronomy for Sustainable Development	260	Alburquerque et al. investigate the effects of biochar addition on wheat yield under various mineral fertilization regimes.	[36]

Authors	Title	Year	Source Title	Cited by	Description	Ref.
Rosales E.; Meijide J.; Pazos M.; Sanromán M.A.	Challenges and recent advances in biochar as low-cost biosorbent: From batch assays to continuous-flow systems	2017	Bioresource Technology	201	Rosales et al. review the challenges and advancements in using biochar as a low-cost biosorbent.	[37]
Lonappan L.; Rouissi T.; Das R.K.; Brar S.K.; Ramirez A.A.; Verma M.; Surampalli R.Y.; Valero J.R.	Adsorption of methylene blue on biochar microparticles derived from different waste materials	2016	Waste Management	201	This study by Lonappan et al. focuses on the adsorption capabilities of biochar microparticles derived from different waste materials, specifically targeting the removal of methylene blue from aqueous solutions.	[38]
Xu K.; Lin F.; Dou X.; Zheng M.; Tan W.; Wang C.	Recovery of ammonium and phosphate from urine as value-added fertilizer using wood waste biochar loaded with magnesium oxides	2018	Journal of Cleaner Production	199	Xu et al. explore the use of wood waste biochar loaded with magnesium oxides for recovering ammonium and phosphate from urine.	[39]
Akdeniz N.	A systematic review of biochar uses in animal waste composting	2019	Waste Management	174	Akdeniz provides a systematic review of the use of biochar in animal waste composting, summarizing current practices and potential benefits.	[40]
Wang S.; Kwak J.-H.; Islam M.S.; Naeth M.A.; Gamal El-Din M.; Chang S.X.	Biochar surface complexation and Ni (II), Cu (II), and Cd (II) adsorption in aqueous solutions depend on feedstock type	2020	Science of the Total Environment	168	Wang et al. investigate the adsorption mechanisms of biochar for heavy metals like Ni (II), Cu (II), and Cd (II), emphasizing the influence of feedstock type.	[41]

5. Future Research in the Wood Waste Biochar to Biofertilizer Applications determined by VOSviewer

The network view map generated by VOS viewer in Figure 8 highlights the interconnectedness of various research topics within the domain of wood waste biochar to biofertilizer applications. Several future research recommendations can be derived from this map to advance the field. First, enhancing linkages between keywords is crucial, as there are gaps and weak connections between key concepts such as "phosphate," "wood waste," "removal," "adsorption," and "composting." Future studies should explore and establish stronger connections between these keywords, investigating their interactions and combined effects to gain a more holistic understanding of biochar's multifaceted role in soil amendment and nutrient recovery.

Second, researchers should focus on under-explored areas highlighted in the map, such as "wood charcoal," "industrial waste," "GHG emission," and "co-pyrolysis." Delving deeper into these topics could uncover new insights and potential applications. For example, studying the role of wood charcoal in reducing greenhouse gas emissions or optimizing co-pyrolysis processes with different feedstocks could yield significant environmental benefits. These areas, being less connected in the current research network, present opportunities for groundbreaking discoveries.

Third, integrating more experimental and field studies is essential, as indicated by the presence of keywords like "experiment," "medium," and "treatment." Future research should bridge the gap between laboratory findings and real-world applications by validating experimental results through field trials. This involves testing biochar's effectiveness in various agricultural settings and conditions to ensure its practical viability and scalability. Such integration will help translate theoretical benefits into tangible improvements in soil health and crop yields.

Fourth, investigating the role of biochar in nutrient cycling is recommended, with keywords like "phosphate," "potassium," "ammonium," and "urine" suggesting an interest in this area. Future studies should focus on how biochar can enhance nutrient availability and retention in the soil, improving crop productivity and sustainability. Specifically, research could explore biochar's ability to adsorb and release essential nutrients over time, its interaction with soil microbes, and its impact on soil fertility under different environmental conditions.

Fifth, optimizing biochar production and application techniques remains a priority, as indicated by keywords such as "feedstock," "pyrolysis," "temperature," and "production." Future research should continue to refine these techniques for higher efficiency, lower costs, and reduced environmental impact. This could involve developing new pyrolysis methods, using different feedstock combinations, and exploring ways to integrate biochar production with other waste management practices. Additionally, innovative application methods, such as combining biochar with other organic amendments, can enhance its effectiveness and broaden its use in various agricultural systems.

Lastly, a multidisciplinary approach involving soil scientists, agronomists, environmental engineers, and policymakers is crucial for developing integrated strategies for sustainable biochar use. The network map shows diverse keywords related to environmental science, agronomy, and waste management, indicating the need for collaborative efforts. By combining expertise from different fields, researchers can develop comprehensive solutions to the challenges faced in biochar research. This includes policy recommendations, best practices for biochar application, and frameworks for evaluating its long-term impacts on soil health and agricultural productivity. By addressing these recommendations, future research can strengthen linkages between key concepts, explore under-explored areas, and optimize biochar applications, contributing to more sustainable and effective use of wood waste biochar as a biofertilizer.

6. Conclusion

This bibliometric analysis provides a comprehensive overview of the research landscape on the application and valorisation of wood waste biochar for biofertilizer. The analysis reveals several key trends, influential studies, and emerging areas of interest that are shaping the field. The growing body of literature underscores the significant potential of biochar to enhance soil fertility, improve crop yields, and contribute to sustainable agricultural practices. The year-wise output analysis shows a steady increase in research publications, reflecting heightened academic and practical interest in biochar applications. Geographical analysis highlights the leading roles of countries like China, the United States, and Canada in driving research and fostering international collaborations. The co-citation and keyword analysis further identify key authors, journals, and recurring themes, providing insights into the influential contributors and pivotal areas of study.

Key recommendations for future research include enhancing linkages between currently underexplored keywords, focusing on the integration of experimental and field studies, and investigating biochar's role in nutrient cycling. Optimizing production and application techniques through multidisciplinary approaches is crucial for advancing the practical use of biochar. Addressing these recommendations will strengthen the research framework, uncover new insights, and facilitate the development of innovative and sustainable biochar applications. In summary, this bibliometric review highlights the vital contributions of wood waste biochar to sustainable agriculture and environmental management. By continuing to explore and address the identified gaps and emerging areas, researchers can further unlock the potential of biochar as a valuable resource for biofertilizer applications, promoting environmental sustainability and agricultural productivity.

Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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All authors contributed equally to the conception, analysis, writing, and final approval of the manuscript. Each author has read and agreed to the published version.

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