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Potential Enhancement of Soil and Sediment Remediation and Bioremediation by Using Biochar Amendment: A Systematic Review

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ABSTRACT

Biochar has gained attention as a viable strategy for soil and sediment remediation in Southeast Asia due to its ability to adsorb heavy metals and organic pollutants, enhance soil fertility, and support sustainable agriculture. This review synthesizes biochar research conducted in Southeast Asia from 2014 to 2024, focusing on pollutant categories, biochar types, and environmental functions. A bibliometric analysis of 103 Scopus-indexed publications assessed research trends, keyword co-occurrences, and institutional and national collaboration networks. Results show an annual publication growth rate of 17.2%, with China, Malaysia, and Sri Lanka as leading contributors. Keywords "biochar," "soil remediation," "heavy metals," and "engineered biochar" appeared most frequently, reflecting emphasis on contaminant immobilization and biochar optimization. Lead, cadmium, and organic pollutants were the primary contaminants addressed. Although engineered and modified biochar has demonstrated enhanced performance for multi-contaminant remediation, significant research gaps remain in the mechanistic understanding of pollutant interactions, large-scale field validation, cost-effectiveness, and integration with complementary technologies. This review represents the first bibliometric evaluation of biochar use for soil and sediment remediation in Southeast Asia and offers insights to support future research direction, collaborative networks, and policy development.

1. INTRODUCTION

Biochar has been well-studied in the past decades, and it is increasingly drawing attention that using biochar can act as a potential remediation strategy [1], especially in soil [2, 3] and sediment [4, 5]. Biochar refers to carbonaceous material generated by the pyrolysis of organic material in a limited oxygen environment [6], and it has been found particularly suitable for improving soil fertility [7], sequestering carbon [8], or immobilizing various contaminants. It has versatile beneficial effects on soil quality, improving [9] as a soil micropollutant for both terrestrial microhabitat and aquatic medium adaptation [10] due to its multifunctional properties such as high surface area, porosity, cation exchange capacity (CEC), and stable carbon structure. Southeast Asia is a land of alarming urbanization, industrial development, and agricultural intensification [11], facing increasingly critical environmental problems. Increased anthropogenic activities such as mining, industrial waste disposal, deforestation, and extensive use of agrochemicals have caused the serious contamination of soil and sediments, especially in marine coastal areas or rivers. 6 The accumulation of heavy metals (e.g., lead, cadmium, mercury), organic contaminants (e.g., pesticides, PAHs), and eutrophication, such as excessive nutrients (e.g., nitrogen, phosphorus), is threatening both ecosystem health and human welfare. Existing soil and sediment remediation strategies, including chemical treatment, soil washing, and dredging, are costly, labor-intensive, and environmentally damaging. In this context, biochar has recently gained attention as a cost-efficient and environmentally friendly alternative to remediate soil and sediment pollution. Its adsorption or immobilization capabilities for pollutants, and its soil amelioration and microbial activity enhancement features render it extremely promising in mitigating the wide variety of environmental problems unique to SE Asia. The expanding literature on biochar applications in the region sheds light not just for its potential as a means of attenuating environmental degradation but also as a potential catalyst for sustainable agriculture and food security, as well as climate change mitigation through carbon sequestration.

Biochar is a charcoal substance enriched in carbon produced from high-temperature processing of organic biomass with little or no air in an inert environment, pyrolysis [12-17]. Biochar has been studied as an excellent environmental management material with a particularly important role in soil amelioration and the promotion of beneficial microbial communities [18, 19]. Specifically, biochar provides a high porosity and large surface area capacity [15, 20] while acting as a substrate for microbial colonization and inducing nutrient retention. These properties make biochar a promising candidate to stimulate the growth of phosphate-solubilizing bacteria (PSB), those microorganisms that convert insoluble phosphate compounds to plant-available forms [21, 22]. The interaction of biochar and PSB has important practical significance in the field of soil remediation, especially for heavy metal-contaminated or phosphorus-deficient soils. The process is an environmentally friendly way of enhancing soil health and fertility [23].

Despite its increasing prominence, the trends and patterns in biochar applications for soil and sediment remediation across Southeast Asia remain fragmented. To bridge this gap, this paper aims to provide a comprehensive review of the developments in this field over the past decade. This review focuses on understanding the types of biochar being used, the pollutants being targeted, and the geographical distribution of biochar research and implementation in the region. By synthesizing findings from multiple studies, this paper will highlight the major advancements and challenges in biochar use, as well as identify future research and policy needs.

The bibliometric analysis was applied to obtain these results, a quantitative technique that enables the systematic study of the research field by analyzing publications, citations, authorship, and other such metadata. Bibliometric analysis can offer clues to research trends by revealing what are the most frequently studied topics, which countries contribute most to biochar research, and how institutions cooperate with each other. What especially recommends bibliometric analysis in the current context is its power to relieve existing fragmentation by quantitatively and visually tracing the profile of a field, revealing hidden patterns, thematic clusters, and under-studied areas (possibly overlooked in traditional narrative reviews). This approach, we suggest, can provide a more unbiased overview of the biochar research status quo in Southeast Asia, permeating those high activity areas as well as the voids that are meant for further study. Bibliometric analysis is specifically helpful in tracing trends in scientific writing [13]. In the biochar application-specific setting, this method provides an overview of pollutants that have been most studied and their association with biochar, the type of biochar used in these studies, and the methodologies applied. Thus, the specific objectives of this review study are: (1) to carry out a bibliometric analysis of biochar research in Southeast Asia from 2014 to 2024 to establish a baseline on research trends, collaboration networks and productivity; (2) to systematically review literature related with application of biochar for soil/ sediment remediation focusing on pollutant types treated, biochar properties and remediation mechanisms; (3) assess emerging form(s) of biochar technology such as engineered or modified BCs including its integration with other technologies supporting remediation; (4) identify knowledge gaps and proposed future research directions to facilitate development of sustainable biochar based technologies for soil/sediment remediation.

2. METHOD

This review study employs a combined method of bibliometric analysis and systematic literature review (SLR), commonly called systematic literature network analysis (SLNA). This method is used to examine the trends and patterns related to studies on soil or sediment remediation using biochar in Southeast Asian countries. The approach is based on research [14], where bibliometric analysis is used to identify trends and patterns in recent studies through citation, keyword, and title-abstract network analysis. Additionally, bibliometric analysis can be applied to identify research gaps.

2.1 Conceptual framework

2.1.1 Data collection

The data collection process for this study is visually represented in Figure 1, and the Scopus database was the primary source used to gather relevant research articles. The data collection was carried out on September 20, 2024, and involved the application of several key filters to refine the results. These filters were refined to select highly relevant literature while preserving the scope of the review. The first filter was regarding keywords, as they are the core of selecting relevant papers for the review. The prior keyword search was performed using the keywords, "soil" OR "sediment" AND "remediation" AND "biochar" OR electrokinetic. This combination of words was intended to tabulate research articles, which deal with biochar or electrokinetics for soil/sediment remediation, as these are the main emphasis areas in the review.

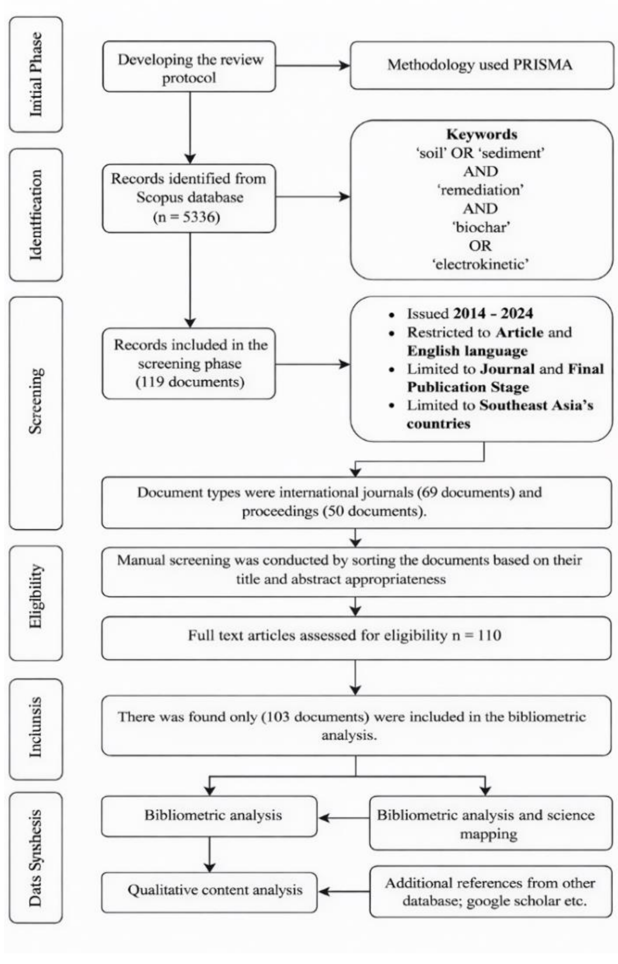


Figure 1. Research framework

The timeline was intentionally compressed to focus on the past decade from 2014 through 2024. This ten-year period facilitated the analysis of recent developments in this dynamic field and that recent work is represented, while older studies were not. The language setting was confined only to accept English to maintain accessibility and analysis integrity. Another key feature of the data collection process was country filter. As this review examines studies carried out in Southeast Asia, the country filter has been manually applied to select for studies from Southeast Asian countries only. In particular, the sample countries used for this review were Malaysia, Sri Lanka, Thailand, Singapore, and Vietnam, while Indonesia, the Philippines, and Laos have also been part of the LMIC Asian countries. Although Sri Lanka is commonly considered to belong to South Asia, it has been added to this review because its environmental situation resembles that of the Southeast Asian countries (e.g., problems related to soil erosion and heavy metal contamination) and research collaboration with institutions in this part of the world. These countries were selected according to the focus of this paper, namely, outlining the extent of literature on soil and sediment remediation within Southeast Asia.

This comprehensive search yielded a total of 5,336 articles, capturing a wide range of publications related to the chosen keywords and topics. However, after applying the various filters, the dataset was carefully refined, leaving only 119 articles that met all the criteria. These 103 articles form the foundation of this review and provide the material for a detailed qualitative analysis. This curated selection of studies offers insight into the prevailing trends and emerging patterns in the realm of soil and sediment remediation, particularly within the unique environmental and geopolitical context of Southeast Asia. It should be noted that this study utilized only the Scopus database for article retrieval. While Web of Science and Google Scholar are also widely used bibliographic sources, Scopus was selected due to its broader journal coverage in environmental science and engineering, robust metadata export capabilities, and compatibility with bibliometric tools such as VOSviewer and Orange. Web of Science was not used due to access limitations, and Google Scholar, although comprehensive, was excluded because of its inconsistent metadata structure and lack of peer-reviewed filtering mechanisms. This constitutes a methodological limitation and may have excluded relevant studies indexed exclusively in other databases.

2.1.2 Data analysis

This review paper employs two software tools, VOSviewer and Orange Data Mining, to construct bibliographic networks, conduct cluster analysis, and create visual maps. VOSviewer is used to examine co-authorship, co-occurrence, and co-citation patterns, enabling the identification of connections between researchers, key terms, and cited references within the literature. In contrast, Orange Data Mining is utilized to analyze the keywords, titles, and abstracts, with the findings displayed as a word cloud, providing a visual overview of the most used terms in the research domain.

2.1.3 Bibliometric analysis and science mapping

The trends and patterns related to research on biochar applications for soil or sediment remediation are visualized using VOSviewer, based on metadata. The analysis covers co-authorship by authors and countries, co-citation, co-occurrence of terms, and the title and abstract. Data analysis is conducted using CSV files, which are then imported into VOSviewer. The generated visualizations include the countries involved in article authorship and the appearance of keywords in each article. These visualizations are crucial for identifying trends in article emergence and citation patterns. Co-citation analysis reveals the connections between countries collaborating in research. Keywords in an article can serve as key indicators of the research trends discussed in earlier studies. There are two types of VOSviewer visualizations for country involvement in research and keyword occurrences: overlay and network visualization. The overlay visualization illustrates the distribution of clusters based on their publication years. In contrast, the network visualization shows the grouping of topics into clusters, each represented by a different color scheme.

VOSviewer was used, and the bibliometric analysis was done using Orange Data Mining. The word cloud was created using Orange Data Mining after downloading the data as a CSV file, showing a visual representation of topics identified inside author keywords as well as in article titles and abstracts. The result of the word cloud analysis provides an easy visualization to distinguish hot topics and cold spots in the dominated but less-dominant places in research. This approach helps illustrate how research attention has fluctuated over time across different areas. To further support the analysis, the annual number of publications and corresponding citation counts have also been visualized for the top 10 contributing countries. Second, this study presented the number of papers published yearly, published by country, and the top 10 citing counts. Such visualizations serve to reveal patterns in the published outputs and the impact of different countries. All of the visualizations in this study can also be found as data in CSV format and were processed and rendered within Origin software. This methodology facilitated a clearer illustration of the publication and citation trends across time, contributing depth to the bibliometric analysis as a whole.

2.2 Qualitative content analysis (VOSviewer)

The analysis-policy content-based of this study is performed based on the same protocol using qualitative research to analyze relevant information produced for each document. This overview presents the potential of soil/sediment treatment with biochar, including the diversity of technologies that are available for remediation as discussed in different studies. The two modes are used in combination for the study to increase its capacity to pick up trends and patterns from articles reviewed by it. This dual approach of strategies could help to shed light on research deficiency and holistically identify the research landscape and knowledge gaps [14].

3. RESULTS AND DISCUSSIONS

3.1 Key principle of technology

The use of biochar in the remediation of polluted soil ode has a connection, because it enhances the soil structure and increases nutrient preservation by containing heavy metals like Pb [24-26]. When the combination with PSB were applied, biochar can further improve soil health through the interaction of phosphorus by making available to plants P forms insoluble compounds which would enhance plant growth and thus contribute to sustaining microbial activity on nutrient cycling [27]. The high CEC biochar may enable immobilization and retention of key nutrients such as phosphorus and nitrogen, offering positive assistance to the plants [28]. Other than that, immobilization of heavy metals like Cd by biochar is very crucial in the reduction of toxic substances' bioavailability and thus their damage to plants and soil [29].

The modified biochar may improve P solubilization by PSB, thereby improving the growth of plants and soil fertility, etc. [30]. The combination of biochar and PSB is quite favourable in degraded/contaminated soils with a low nutrient supply and high levels of toxic metals [31, 32]. The interactions between biochar and PSB have shown the synergetic effect (additive interaction) in bioremediation, which has now been integrated into the long-haul period to restore the ecosystems [32, 33]. The biochar is characterized by a high content of organic carbon, porosity, and water retention [34]. These properties and their potential to host loads of essential nutrients (Ni, P, and K) for the plants make biochar a suitable environment for plant growth as well as microbial colonization [35]. In addition, biochar also exhibits the unique property of immobilizing microorganisms by providing an active site and a favourable environment for living, which increases microbial activity to break down soil contaminants [36, 37]. As a microbial carrier, biochar enriches the colonization of microbes, especially around plant roots and mediates better nutrient cycling and overall soil health [38]. Several mechanisms have also been proposed for the immobilization, such as adhesion, pore filling, electrostatic interactions, and covalent bonding that contribute to the enhancement of substrate-adsorbent contact [37, 39]. Furthermore, biochar as a substrate has also been confirmed to be an excellent substance to improve PSB performance for polluted soils remediation [40, 41]. It was observed that biochar also contributes to the growth of plants in relatively unfavourable conditions like HM-polluted soils [42, 43]. Modified biochar has enhanced contaminant adsorption ability, and it provides protection for microorganisms against toxicants when combined with metals such as Fe_3O_4 [44, 45]. Biochar is effective in immobilization of microorganisms and dissolved carbon, but the porosity, surface area, and nutrient content of biochar also play an important role in dictating its efficiency for remediation processes, since soil pH and concentration of contaminants are also significant determinants.

3.2 Bibliometric analysis results

3.2.1 Research trends

The research trends in biochar applications for soil or sediment remediation in Southeast Asia over the past decade are illustrated in Figure 2. The graph, generated using Origin software, depicts the number of publications per year from 2015 to 2023. The trend started with 7 publications in 2015, followed by a slight decline to 5 publications in 2016. There is a steady but modest increase in subsequent years, with 6 publications each in 2017 and 2018. A significant rise is observed in 2019 and 2020, with 11 publications each year. This upward trajectory continues with a notable increase to 18 publications in 2021, followed by 19 publications in 2022. The peak is reached in 2023 with 20 publications. This data indicates a growing interest and increasing research activity in the field of biochar applications for environmental remediation in Southeast Asia, reflecting the escalating recognition of biochar's potential benefits and the increasing efforts to address soil and sediment contamination in the region.

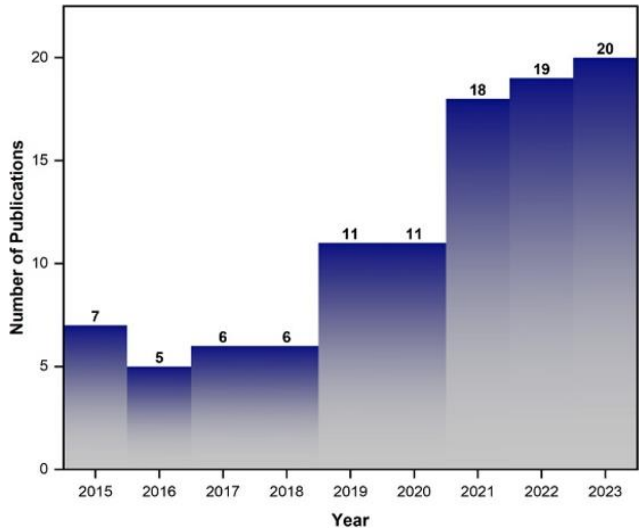


Figure 2. Number of publications per year

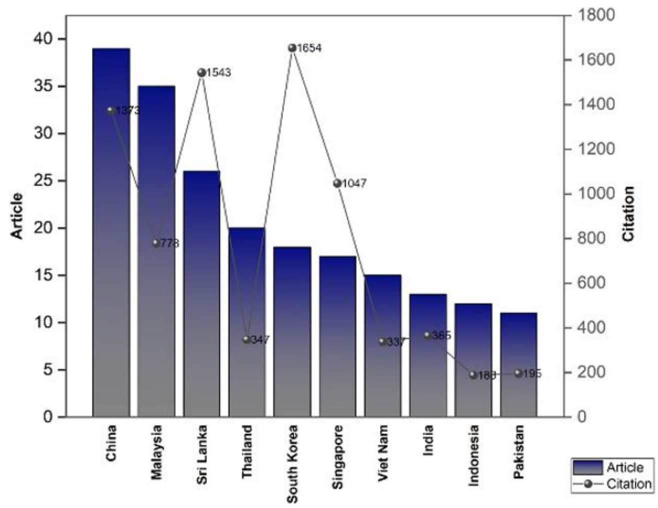


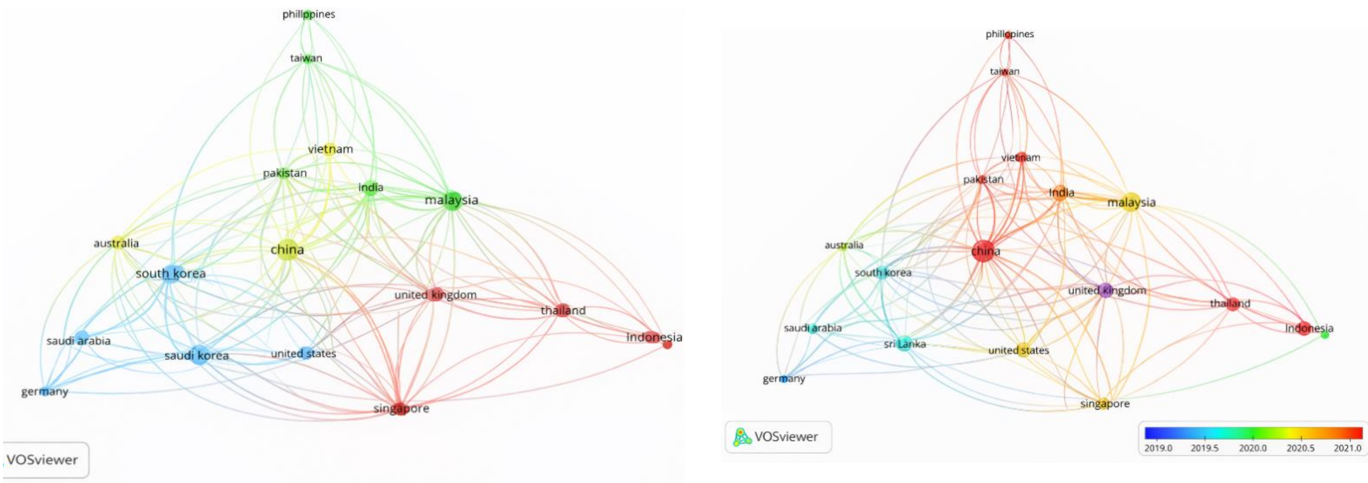
Figure 3. Number of documents linked to citation counts for the top 10 countries

The research trends related to biochar applications for soil and sediment remediation emphasize the top ten countries based on their publication and citation metrics, as shown in Figure 3. Leading the field, China has the highest number of published articles, exceeding 35, along with a significant citation total of 1,373, highlighting the country's substantial contribution to biochar research. Following closely, Malaysia and Sri Lanka each have more than 25 published articles, although their citation counts differ: Malaysia has 778 citations, while Sri Lanka boasts 1,543, indicating variations in the impact and outreach of their respective research efforts. South Korea stands out with the highest citation count of 1,654, despite having fewer publications than the leading countries. This suggests a strong influence per article published. Thailand and Singapore, with publication numbers slightly under 30, show moderate citation totals of 347 and 1,047, respectively. Meanwhile, Vietnam, India, Indonesia, and Pakistan contribute fewer articles but still maintain significant citation counts, reflecting their active engagement in the biochar research domain. This visualization shows China's dominant position in terms of both the volume and quality of research output, while other Southeast Asian nations also play critical roles in advancing biochar studies, particularly regarding the impact of citations per publication.

The differing trends in publication and citation counts further highlight the distinct regional research focuses and their respective global influences.

3.3 Citation analysis

The co-authorship analysis reveals a strong concentration of biochar research for soil and sediment remediation in Southeast Asia and nearby regions. The co-authorship network is an indicator of collaborative research, where authors work together on proposed topics [46]. China leads with 39 publications, likely due to its significant focus on addressing environmental pollution and soil contamination from industrial activities (Figure 4(a)). Malaysia follows closely with 35 documents, reflecting its interest in sustainable agriculture and soil health improvement. Sri Lanka ranks third with 26 publications, likely driven by efforts to combat soil degradation. Thailand, South Korea, and Singapore also contribute notably, with 20, 18, and 17 documents, respectively, indicating their involvement in innovative environmental solutions. Vietnam, India, and Indonesia show moderate contributions with 15, 13, and 12 documents, emphasizing their regional focus on land restoration and pollution management. Countries outside of Asia, such as the United Kingdom, the United States, and Australia, also play roles in global biochar research, each contributing around 10 publications. These collaborations reflect shared interests in sustainable land management. Nations like Japan, the Philippines, Taiwan, and Germany, with five publications each, suggest smaller but specialized research activities. Saudi Arabia also appears with five documents, likely focusing on environmental sustainability. The overall data underscores the importance of international collaborations in advancing biochar research. Together, these countries form a diverse and expanding network addressing critical environmental challenges through biochar applications.



(a) (b)

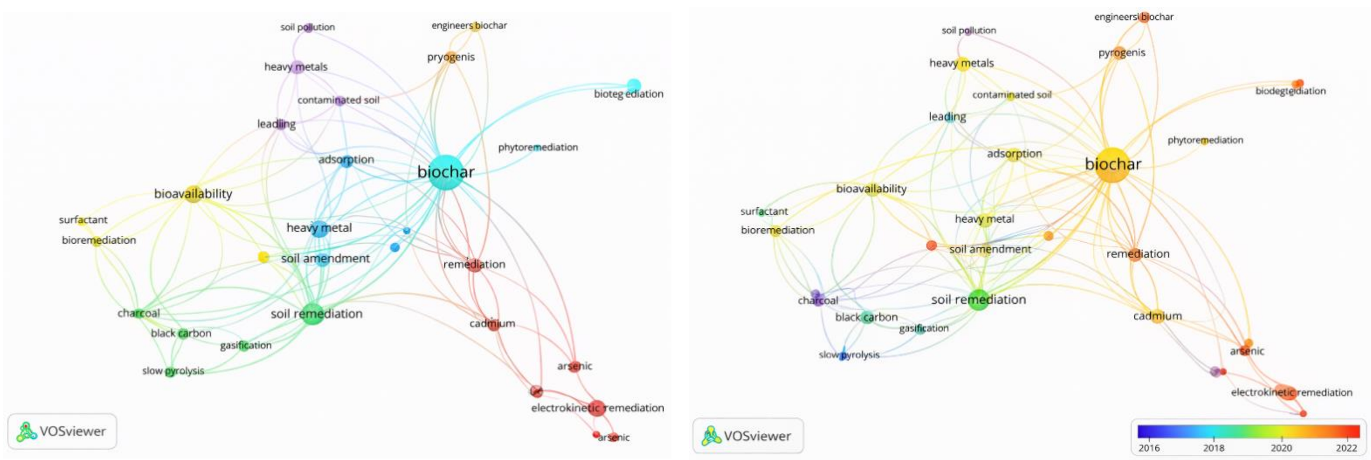
Figure 4. Network of collaboration between countries (a) Network; (b) Overlay visualization

The co-authorship analysis of biochar research highlights significant contributions from various countries, revealing trends in publication activity and timing. China leads with 39 documents and an average publication year of 2021.41, demonstrating its ongoing commitment to addressing environmental challenges through biochar technologies (Figure 4(b)). Malaysia follows closely with 35 publications, an average of 2020.57 per year, indicating its active role in sustainable land management practices. Sri Lanka, with 26 documents and an earlier average publication year of 2019.65, suggests that its research efforts in biochar may have peaked earlier. In contrast, Thailand, Vietnam, and Indonesia show recent engagement, with average publication years around 2021, reflecting a growing recognition of biochar's potential for remediation. South Korea and the United Kingdom had an earlier focus on biochar research, with average publication years in 2019, possibly indicating a shift in their research priorities. Australia and Singapore also maintain moderate contributions with average years around 2020, suggesting recent but steady involvement. Emerging countries like India and the Philippines, with average publication years of 2022, showcase an increasing interest and rapid advancements in biochar applications. Pakistan's contributions are notable, with an average of 2021.54, suggesting a focused commitment to this area of research. The United States and Germany demonstrate consistent but slightly earlier research activity, averaging around 2020. Countries like Japan, Taiwan, and Saudi Arabia show a steady output, with average years between 2019 and 2021. The data illustrate a dynamic and expanding research landscape where established nations continue to contribute alongside emerging players. This indicates a growing collaborative effort to explore biochar's applications in addressing soil and sediment remediation challenges. The geographical spread of research not only highlights regional engagement but also emphasizes the global recognition of biochar's significance in environmental sustainability. This analysis underscores the importance of international collaboration in advancing knowledge and practical applications of biochar technologies.

3.4 Bibliometric analysis using VOSviewer

The co-occurrence analysis of author keywords using VOSviewer, with full counting, highlights key research trends in biochar applications for soil and sediment remediation. Out of 427 keywords, 31 met the threshold of appearing at least three times, which emphasizes the core focus areas in this field (Figure 5(a)). Keyword co-occurrence analysis focuses on examining the relationships between words to identify similarities and infer key research areas within a subject [47]. The most frequent keyword, "biochar," appearing 42 times, underlines its central role in this research area. Other prominent keywords like "heavy metals" (8 occurrences), "bioavailability" (9 occurrences), and "soil remediation" (15 occurrences) demonstrate the ongoing concerns about soil contamination and the efforts to develop sustainable remediation strategies. The clustering of keywords provides further insight into specific subfields, such as the group involving terms like "soil," "adsorption," and "heavy metal remediation," which suggests a focus on biochar's ability to reduce the mobility of contaminants in soil. Similarly, another cluster involving keywords like "black carbon," "charcoal," and "pyrolysis" points to research on biochar production methods and optimization for environmental applications.

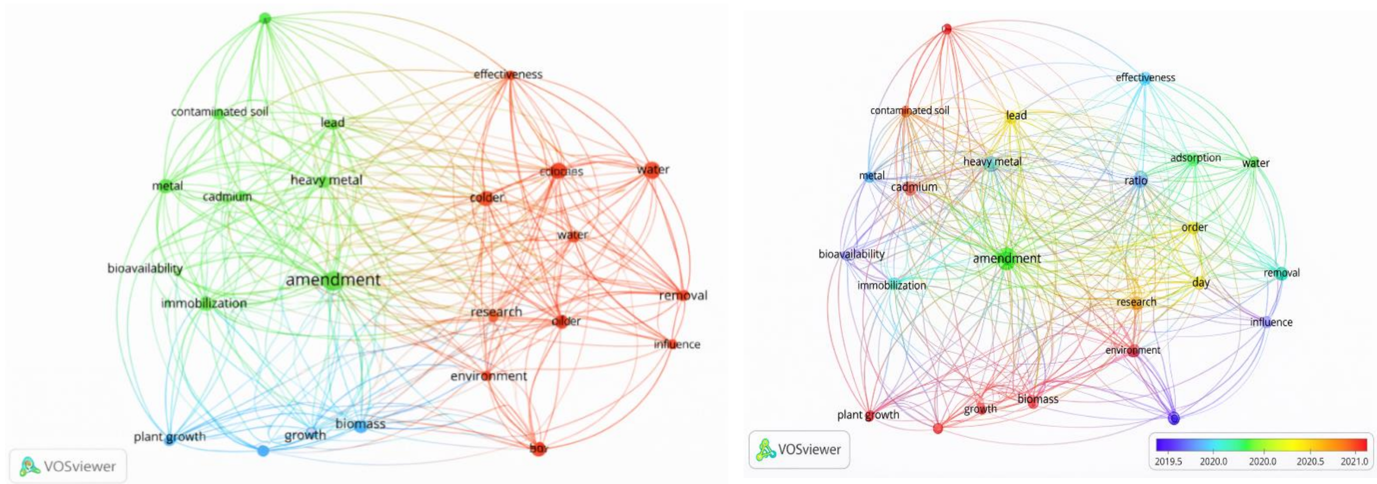
Additionally, the analysis highlights emerging areas of interest, such as "engineered biochar" and its growing application in targeted environmental remediation. Other keywords like "bioremediation," "phytoremediation," and "environmental remediation" show that biochar research intersects with a wide range of remediation techniques, indicating its versatility in addressing multiple pollutants. The frequent appearance of "adsorption" and "remediation" suggests that biochar is integrated into various approaches for environmental cleanup. Overall, this keyword analysis paints a detailed picture of the research landscape, showing a strong focus on biochar’s role in soil remediation, pollutant adsorption, and the development of innovative techniques. The clustering of related terms suggests a collaborative and interdisciplinary approach, as researchers explore new ways to improve the effectiveness of biochar in addressing soil and sediment contamination.



(a) (b)

Figure 5. Co-occurrence keywords: (a) Network visualization and (b) Overlay visualization

The overlay visualization created using VOSviewer shows the temporal distribution of keywords in research related to biochar applications for soil and sediment remediation, as shown in Figure 5(b). The map uses color coding to represent the year of publication, with blue representing earlier years (around 2016) and red indicating more recent years (up to 2022). This gradient allows for an easy identification of emerging research areas as well as established ones, providing insight into how the research landscape has evolved over time. At the center of the visualization is the keyword "biochar," which appears as a central node with connections to numerous other terms, highlighting its foundational role in the field. The connections radiate from this central node to various other keywords, reflecting the interdisciplinary nature of biochar research. Keywords such as "soil remediation," "adsorption," and "heavy metals" are linked closely with "biochar," signifying ongoing investigations into its ability to remediate contaminated environments. These keywords, colored in yellow and light green, indicate that research on these topics has been consistently active over the last several years, emphasizing the persistence of these themes in the literature. The distribution of other keywords also reveals how certain research topics have developed more recently. For instance, terms like "engineered biochar" and "biodegradation" are colored in orange and red, indicating that research into these areas is gaining traction in the more recent years. This suggests a growing interest in optimizing biochar properties to enhance its environmental applications, particularly through engineering modifications that can improve its efficacy in remediation processes. On the other hand, older research topics appear in blue and green. Keywords such as "black carbon," "charcoal," and "gasification" appear in blue, showing that earlier research focused heavily on understanding the production and characteristics of biochar. These older keywords reflect foundational studies that helped establish biochar’s role in environmental remediation. Additionally, "slow pyrolysis" and "surfactant" are also earlier concepts, likely linked to the initial studies on biochar production methods and their interaction with soil pollutants. The visualization also highlights emerging pollutants of concern. Keywords like "lead," "cadmium," and "arsenic" are colored closer to green and yellow, suggesting that these specific contaminants have been the focus of studies for some time, but the research interest persists, particularly in developing remediation methods using biochar. Similarly, the keywords "electrokinetic remediation" and "phytoremediation," which are shown in green and yellow, demonstrate a continued interest in integrating biochar with other advanced remediation technologies to improve the removal of contaminants from soil. The recent emergence of topics such as "engineered biochar" suggests that the field is expanding into more specialized and innovative approaches, while foundational studies on biochar’s properties and interactions remain relevant. The temporal distribution of keywords offers a comprehensive picture of how biochar research has progressed and where it is headed, with the ongoing focus on its applications for addressing environmental contamination.



(a) (b)

Figure 6. Co-occurrence of key terms within the titles and abstracts (a) Network; (b) Overlay visualization

The analysis of text data from titles and abstracts reveals distinct clusters and keyword occurrences, reflecting key themes in biochar research. Cluster 1 focuses on adsorption processes and environmental conditions, with "removal" (28 occurrences) standing out, indicating the central goal of eliminating contaminants (Figure 6(a)). High-frequency terms such as "ratio," "water" (both 21 occurrences), and "adsorption" (18 occurrences) suggest ongoing efforts to optimize biochar's adsorption properties, especially in water and soil. Keywords like "effectiveness" and "environment" reflect a focus on the efficacy of biochar in various settings. Cluster 2 emphasizes contaminants, particularly metals, with "amendment" (39 occurrences), highlighting biochar's role in soil improvement. "Heavy metal" and "removal" (28 occurrences each) point to the widespread concern over metal contamination. Terms like "lead," "cadmium," and "zinc" indicate a focus on mitigating these toxic elements. The occurrence of "immobilization" and "bioavailability" shows an interest in reducing metal mobility in soils. Cluster 3 centers on biomass and plant interactions, with "biomass" (24 occurrences) and "plant growth" reflecting biochar's effects on agricultural productivity. The frequent use of "pot experiment" (13 occurrences) underscores the reliance on controlled experiments to test biochar's impacts, supporting its potential for environmental remediation and agricultural use.

The overlay visualization analysis highlights the evolving focus of biochar research based on keyword occurrences and average publication years. Keywords like "adsorption" (2020.1) and "removal" (2020.04) suggest that recent studies have centered around biochar's ability to remove contaminants, reflecting increased concern over environmental pollution (Figure 6(b)). The relatively recent emphasis on "environment" (2021.56) and "water" (2020.23) indicates a shift toward applying biochar in broader environmental contexts, particularly for water treatment. Terms like "effectiveness" (2019.93) and "research" (2020.87) point to a focus on assessing biochar's performance in real-world scenarios during this period. Continued interest in metal contaminants is evident with keywords such as "cadmium" (2021), "lead" (2020.52), and "heavy metal" (2019.67), showing that heavy metal remediation remains a key priority. The consistent presence of terms like "contaminated soil" (2020.77) and "immobilization" (2020.04) reflects ongoing efforts to reduce metal mobility in soils using biochar. Earlier keywords such as "amendment" (2020.25) and "bioavailability" (2018.75) suggest that foundational work on biochar's role in reducing pollutant bioavailability had already been established. Meanwhile, the more recent focus on "biomass" (2021.16) and "plant growth" (2021.07) indicates increasing interest in biochar's agricultural applications. This shift towards agricultural productivity reflects a broader recognition of biochar's potential beyond remediation. The data shows a progression from initial studies on biochar's core properties to more recent explorations of its environmental and agricultural impacts, demonstrating the expanding scope of biochar research.

3.5 Word cloud analysis

The word cloud generated by Orange Data Mining identifies critical terms prevalent [14] in biochar research, highlighting themes centered around its application in soil improvement and environmental remediation. Prominent words such as "soil," "biochar," and "remediation" signify that much of the existing literature focuses on how biochar can enhance soil properties and remediate contaminated environments, as shown in Figure 7. Additionally, the frequent occurrence of terms like "heavy metal" and "adsorption" underscores the importance of biochar's role in mitigating heavy metal contamination, indicating a significant area of research aimed at addressing environmental pollutants. The analysis also reveals the significance of related concepts such as "pollution," "contaminated," and "sustainable," demonstrating the growing concern for environmental issues and the pursuit of sustainable practices within the context of biochar applications. Moreover, the word cloud introduces emerging themes, including "electrokinetic," "biodegradation," and "bioremediation," which indicate innovative approaches being explored to enhance biochar's efficacy in remediation efforts. Terms such as "waste," "carbon," and "biomass" reflect the holistic perspective researchers are adopting in tackling issues related to waste management and carbon sequestration. Overall, the word cloud presents a comprehensive overview of the diverse and evolving landscape of biochar research.

In contrast, the co-occurrence analysis from VOSviewer offers a more structured view of the relationships between these key terms, revealing a strong interconnectedness among the various themes identified in the word cloud. Notably, VOSviewer emphasizes "biochar" as a pivotal term within the literature, aligning with its prominence in the word cloud. The term "phytoremediation" appears prominently in VOSviewer, highlighting a parallel trend where researchers explore the synergies between biochar and plant-based remediation strategies. Furthermore, terms like "microbial," "chemical," and "organic" point to the intricate biological and chemical processes facilitated by biochar, suggesting a deeper investigation into its interactions within the ecosystem. Both analyses underscore the multifaceted nature of biochar research, indicating that scholars are increasingly investigating various methodologies and applications. This convergence of themes points to a robust and dynamic field of study, where the interplay between biochar and diverse remediation techniques is gaining momentum. Ultimately, these findings suggest a collective goal within the research community to advance sustainable practices and improve environmental restoration efforts through innovative biochar applications.

Figure 7. Word cloud of author keywords

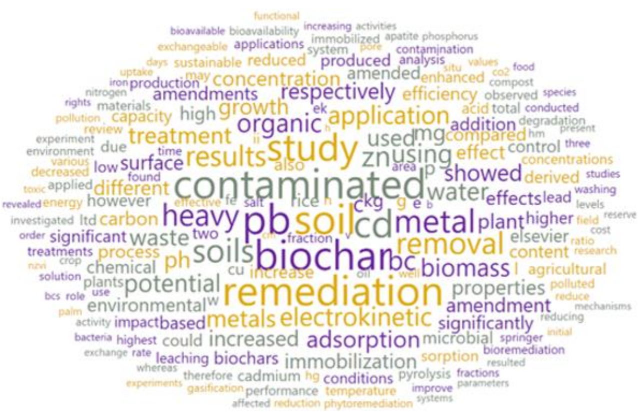


Figure 8. Title and abstract

The word cloud analysis reveals key research themes in biochar studies based on word frequency in titles and abstracts, depicted in Figure 8. The most frequent term, "soil" (612 occurrences), underscores the central focus on soil remediation, while "biochar" (497 occurrences) highlights the material's significance in this context. Words like "contaminated" (141 occurrences) and "remediation" (139 occurrences) show a strong focus on addressing polluted environments, particularly heavy metal-contaminated soils. Specific metals like "Pb" (129 occurrences), "Cd" (119 occurrences), and "Zn" (83 occurrences) further reflect the concern with toxic metal contamination. Terms like "removal" (90 occurrences) and "adsorption" (66 occurrences) emphasize biochar's role in removing contaminants, while the presence of "water" (71 occurrences) suggests biochar's application in water purification as well. The frequent mention of "biomass" (69 occurrences) and "organic" (73 occurrences) indicates a focus on biochar production from organic materials. Words like "study" (117 occurrences) and "results" (82 occurrences) point to the extensive experimental research in this field. The use of terms like "potential" (69 occurrences) and "efficiency" (46 occurrences) reflects ongoing assessments of biochar's effectiveness, particularly in enhancing environmental sustainability. Lastly, words like "growth" (61 occurrences) and "plant" (56 occurrences) signal interest in biochar's agricultural benefits. This data illustrates biochar's broad applications across remediation, agriculture, and environmental management.

The comparison between the word cloud from Orange Data Mining and the VOSviewer keyword analysis reveals common themes in biochar research, such as the central focus on biochar and soil for remediation, especially concerning heavy metals like lead and cadmium, and processes like adsorption and removal. Both analyses highlight biochar's role in addressing soil contamination and its potential to improve soil health. However, VOSviewer places more emphasis on specialized remediation techniques like phytoremediation and engineered biochar, showcasing advanced applications, whereas the word cloud from Orange Data Mining focuses more on general research processes, with frequent terms like study, results, and using. This indicates that VOSviewer provides a more detailed view of specific remediation strategies, while the word cloud offers a broader perspective on biochar's experimental applications and outcomes.

3.6 Qualitative analysis

Rapid industrialization and inappropriate human activities have led to widespread environmental pollution, posing significant health risks [48, 49]. The severity of pollution varies with the nature of contaminants [50, 51]. Bioremediation is widely regarded as the most effective, economical, and eco-friendly method for sustainable pollution treatment [52]. Biochar, produced through pyrolysis with limited oxygen, contains key elements like carbon and nitrogen [53]. It helps decompose organic contaminants and bind heavy metals while retaining soil moisture, making it highly effective for soil and sediment remediation [54, 55].

The top five highly cited articles, as shown in Table A1, in biochar research highlight diverse technologies and applications for soil remediation. The first article investigates steam-activated biochar derived from invasive plant species, focusing on its effectiveness in removing the veterinary antibiotic sulfamethazine from water [56]. Slowing pyrolysis and using steam activation, the research realizes an improvement in the biochar's adsorption ability, which can be used to remediate pharmaceutical contamination in both soil and water. The second paper presents a prediction model for immobilization efficiency of biochar added with heavy metals in polluted soils by a machine learning algorithm in contaminated soil [57]. Through a random forest model based on various biochar and soil properties, the study simplifies the complex relationships and provides a predictive framework for biochar application to be used in environmental remediation.

Thirdly, the gasification biochar effect on soil quality is presented by the third article, focusing on the impact of this waste material in trace metal behavior and microbial community [58]. This study also provides evidence of biochar to improve the overall soil health, through its influence on metal bioavailability and stimulation of microbial activity, leading to enhanced remediation efficiency. In the fourth article [33], the wood waste biochar was investigated as an environmentally friendly admixture for cement-based construction materials using dredged sediments. This novel application could improve the mechanical performance of construction materials and immobilize hazardous elements in an environmentally friendly recycling manner. Finally, the fifth article examines the potential of bioenergy biochar as an immobilizing agent of lead and arsenic in contaminated soils [59]. Through characterizing biochar produced in bioenergy systems, the paper illustrates the potential as a soil decontamination approach and shows that applications of biochar can be the effective way of remediating contaminated soils.

4. FUTURE PERSPECTIVE

Additional biochar research should focus on engineered (modified) biochars specifically designed to function as effective PSB carriers. Recent studies have investigated composite materials with enhanced abilities for both phosphate solubilization and heavy metal immobilization [60, 61]. Such developments involve modifying the chemical and structural properties of biochar, for example, by introducing metal oxides or modifying surface functional groups. These developments could improve soil quality and may indicate new methodologies for precise amelioration of different types of damaged soils. In addition to chemical modification, integration of the chemical and biological clean-up capacity into biochar would appear as a good approach in future studies. The synergistic effect of biochar immobilizing heavy metals and stimulating microbial activity, through promoting PSB, represents an integrated remediation of metal-contaminated soils [62, 63]. This "superfund" approach has the advantage that it is chemically amenable to diverse forms of pollution, including organic pollutants and nutrient imbalances, and this possibly constitutes an example of how biochar could be used for environmental remediation more extensively [64, 65].

Despite these promising laboratory findings, large-area long-term field studies are urgently needed to confirm the sustainability and practical applicability of biochar under various environmental conditions. Most of the studies have been limited to laboratory conditions, so that many other influencing factors, such as those of the natural environment, would not be expected. Field-level and/or field-scale investigation is required to assess the persistence of beneficial impacts for biochar (e.g nutrient retention, long-term contaminant immobilization), particularly under different climatic conditions and soil types [66]. Furthermore, despite the great emphasis on P use efficiency, it is necessary to evaluate in further studies the effect of biochar on other principal macronutrient nutrient management (N and K). Additional insights on the contribution of biochar in nutrient cycling would also provide an add-on to the evidence base for its potential use as a sustainable farming option, particularly in areas with impoverished soil [67]. With the growing challenges related to climate change, there is a rapidly growing interest in its likely role for climate-smart agriculture. Biochar is also known to be capable of sequestering carbon in the soil, reducing atmospheric CO_2. Furthermore, its commitment to the enhancement of soil properties and resistance against climate-dependent stress factors such as droughts and high temperatures makes biochar a hindering candidate to minimize the adverse effects of climate change on agricultural systems [68]. Cross-disciplinary research through integration among soil science, microbiology, environmental engineering, and biotechnology would be an exciting future for development in biochar systems. These joint studies would be able to provide an overview of the modalities of use of forms and biochar application, as well as a broader spectrum of technologies benefited the soil ecological status. Ecosystem reconstruction through its reintroduction in agro-ecosystems could shape it [69-71].

5. CONCLUSION

This review provides a comprehensive synthesis of recent research trends in the application of biochar for soil and sediment remediation in Southeast Asia. Bibliometric and qualitative analyses reveal an increasing volume of publications over the past decade, with China, Malaysia, and Sri Lanka emerging as the most active contributors. The keyword analysis identified "biochar," "soil remediation," and "heavy metals" as dominant themes, underscoring the emphasis on sustainable strategies to mitigate environmental contamination. Among the technologies reviewed, biochar demonstrates considerable efficacy in immobilizing heavy metals, enhancing soil structure, and supporting microbial activity. Additionally, engineered biochar and electrokinetic remediation techniques have shown promise in addressing site-specific pollutants, indicating a shift toward more targeted and integrative approaches. These findings reinforce biochar's potential as a multifunctional and sustainable tool for addressing complex environmental challenges in the region.

The efficacy of biochar for remediation applications is due to its physicochemical properties, such as a high surface area and pore volume, and high cation exchange capacity that can adsorb contaminants while improving soil fertility and texture. These properties also lead to favorable conditions for microbial colonization and plant growth, thus rendering biochar a suitable amendment for the rehabilitation of degraded and contaminated soils. (Biochar to Enhance Soil-Related C sequestration) In view of the fact that Southeast Asia is currently undergoing rapid industrialization with increased land-use pressure, the application of biochar in SE As could be a more socio-economically and environmentally friendly means for reclamation compared to traditional waste management methods. Future work on novel biochar formulations and helping the integration of these with other complementary biogeochemical approaches could further broaden their applicability and significance in sustainable agriculture and environmental management.

Notwithstanding the strengths of this study, several limitations must be acknowledged. First, the bibliometric analysis was confined to literature indexed in the Scopus database and limited to English-language publications, potentially omitting relevant research disseminated through other academic databases or published in regional languages. Second, publication data from several Southeast Asian countries remain limited, which may result in an underrepresentation of national or local research contributions. Third, although the study utilized overlay visualization to explore temporal trends in keyword usage, such representations provide only generalized insight. The inclusion of a longitudinal analysis using bar or line graphs to track the annual frequency of the most influential keywords would yield a more robust understanding of the evolution of research priorities over time. Lastly, while the study includes a co-authorship network at the national level, it does not incorporate institutional-level collaboration analysis. Institutional network mapping is crucial for identifying centers of research excellence, understanding the distribution of scientific capacity, and fostering targeted inter-organizational collaborations. Future research should address these gaps by employing multi-database searches, multilingual inclusion criteria, and more granular network analyses to deepen the understanding of scholarly dynamics in biochar-related research.

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APPENDIX

Table A1. Top 5 studies with highest citations

Title	Citation Counts	Purpose	Technology in Soil Remediation	Reference
Enhanced sulfamethazine removal by steam-activated invasive plant-derived biochar	337	The research evaluates the effectiveness of steam-activated biochar from invasive plants in removing sulfamethazine (SMT) from water, focusing on biochar production, sorption capacity, and the influence of pH and biochar properties on SMT removal.	The study processed invasive burcucumber plants into fine powder, pyrolyzed at 300°C and 700°C to produce biochar, and steam-activated them for 45 minutes at the same temperatures. Batch experiments assessed the sorption capacity of this biochar for sulfamethazine (SMT), examining the effects of solution pH and biochar properties. Adsorption isotherm models were applied to analyze sorption data and elucidate SMT removal mechanisms.	[56]
Prediction of Soil Heavy Metal Immobilization by Biochar Using Machine Learning	190	The research aims to develop a machine learning model to predict biochar's effectiveness in immobilizing heavy metals, identifying optimal conditions for soil remediation and promoting environmental sustainability.	The study analyzed 20 biochar and soil property variables to assess their correlation with heavy metal immobilization efficiency. A random forest model was developed to predict this efficiency, with performance evaluation confirming its reliability. A graphical user interface was created to facilitate the tool's use in identifying optimal biochar application conditions for soil remediation.	[57]
Effect of gasification biochar application on soil quality: Trace metal behavior, microbial community, and soil dissolved organic matter	167	The research investigates how gasification biochar affects soil quality, focusing on trace metal behavior, microbial dynamics, and dissolved organic matter, to explore its potential in soil remediation and sustainability.	The study examined the effects of gasification biochar on soil quality by analyzing trace metal behavior and microbial communities. Methods included $CaCl_2$ extraction for metal bioavailability, pH-stat leaching for buffering and metal solubility, FAME analysis for microbial activity, and fluorescence EEM with PARAFAC modeling for dissolved organic matter. Statistical analyses identified significant impacts on soil health and microbial dynamics.	[58]
The roles of biochar as green admixture for sediment-based construction products	160	The research explores wood waste biochar as a green admixture to enhance the mechanical performance of cement-based products from dredged sediments. It assesses sediment properties for eco-friendly construction use and examines biochar's role in improving cement hydration and contaminant immobilization, promoting sustainable recycling in construction.	The study explored wood waste biochar as a green admixture in cement-based products from dredged sediments. Three marine sediments were characterized, mixed with biochar, and tested for compressive strength. Toxic element leachability was assessed via TCLP, while X-ray diffraction and porosimetry analyzed mineralogy and microstructure, aiming to validate sediment recycling for eco-friendly construction materials.	[33]

Characterization of bioenergy biochar and its utilization for metal/metalloid immobilization in contaminated soil	128	The research aims to characterize bioenergy-derived biochar and assess its impact on arsenic (As) and lead (Pb) mobility in contaminated soils. It evaluates biochar's effectiveness in reducing Pb extractability while examining the potential mobilization of bioavailable As, focusing on how biochar properties influence metal(loid) immobilization.	The research evaluated the effectiveness of bioenergy biochar (BBC) in immobilizing lead (Pb) and arsenic (As) in contaminated soils. Soil properties (pH, electrical conductivity) and metal mobility (via ammonium acetate extraction and ICP-OES) were analyzed. Biochars produced through various thermal techniques were assessed for their impact on metal immobilization. Sequential extraction and geochemical modeling were used to simulate Pb speciation, linking biochar characteristics to Pb and As immobilization for potential soil remediation applications.	[59]