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REVIEW

Biochar Production from Sugarcane Residues: Pathways toward Low-Carbon Environmental Technologies

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ABSTRACT

This study presents a bibliometric analysis and scientific mapping of the valorization of sugarcane waste for biochar production and its integration with titanium dioxide (TiO_2) in environmental applications. The analysis covers the period from 2014 to 2025 and is based on 1,597 unique peer-reviewed documents retrieved from the Scopus and Web of Science databases and systematically processed using Bibliometrix.The results indicate a significant expansion in scientific output, particularly after 2021. Despite annual fluctuations, the overall trend remained one of growth throughout the analyzed period. China, India, and Brazil are the most productive countries among the institutional entities registered in the databases consulted; the Egyptian Knowledge Bank (EKB), the Indian Institute of Technology (IIT System), and Guangxi University stood out, reflecting the metadata indexed by the databases used. Scientific output consists predominantly of Single-Country Publications (SCP), although countries such as Pakistan, Australia, and the United States exhibit higher levels of international collaboration.

KEYWORDS biochar, titanium dioxide, sugarcane residues, agro-industrial waste, photocatalysis

1. Introduction

In recent decades, the reuse of agro-industrial waste has emerged as a key strategy in the development of sustainable technologies, particularly within the context of the circular economy and the mitigation of environmental impacts (Khare *et al.* 2021; Silalertruksa *et al.* 2022).

The expansion of agricultural and industrial activities has led to the generation of large volumes of lignocellulosic residues. When improperly managed, these wastes can cause significant environmental impacts, including greenhouse gas emissions, soil degradation, and water contamination (Chandra *et al.* 2021; Adiansyah 2025).

Among emerging technological alternatives, the production of biochar from residual biomass via pyrolysis has gained considerable attention. Pyrolysis is a thermochemical process conducted under limited oxygen conditions, enabling the conversion of organic waste into stable carbon-rich materials with high potential for environmental applications (Doumer *et al.* 2015; Zhai *et al.* 2024).

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Biochar exhibits high chemical and structural stability, allowing long-term persistence in the environment. In addition, its physicochemical properties make it highly suitable for environmental remediation processes (Aluthge *et al.* 2025).

These properties are strongly influenced by the feedstock and pyrolysis conditions, particularly temperature, heating rate, and residence time. Such parameters directly affect structural stability, specific surface area, pore distribution, and surface functionalization, which in turn determine the material's performance in environmental applications (Zhang *et al.* 2017; Chaudhary *et al.* 2023).

As a result, biochar typically exhibits high adsorption capacity and surface reactivity, expanding its applicability across various environmental domains (Barría *et al.* 2025).

In the specific case of sugarcane bagasse, a widely available residue in the agro-industrial sector, particularly in Brazil, biochar production represents a strategic alternative for waste valorization and the reduction of environmental liabilities associated with the sugarcane industry (Carolino *et al.* 2025).

Brazil is one of the world's largest producers of sugarcane, generating substantial quantities of lignocellulosic residues that can be converted into high-value materials through sustainable thermochemical processes (Aluthge *et al.* 2025).

Beyond its use as a soil amendment, biochar has demonstrated strong potential as an adsorbent material for the removal of organic and inorganic contaminants. It has been widely applied in the removal of pharmaceuticals, pesticides, dyes, and heavy metals from aqueous systems and contaminated soils (Barría *et al.* 2025).

Studies on sugarcane bagasse-derived biochar have demonstrated significant capacity for retaining herbicides and other organic compounds, with performance strongly influenced by particle size, surface area, and application rate, highlighting the importance of structural properties in sorption processes (Silva *et al.* 2018; Mielke *et al.* 2022).

Furthermore, the interaction of biochar with soil nutrients can modify the availability of phosphorus and other essential elements, influencing nutrient retention, adsorption processes, and fertilizer efficiency (Domingues 2014).

Biochar application can also alter soil pH, cation exchange capacity, and the retention of nutrients and trace elements, thereby modifying soil chemistry and plant nutrient uptake (Aluthge *et al.* 2025; Carolino *et al.* 2025). These characteristics reinforce its role as a multifunctional material capable of improving soil quality while mitigating environmental contamination.

In addition to adsorption and soil conditioning applications, recent studies have explored the use of biochar as a catalytic support or structural component in hybrid materials designed for environmental remediation.

In this context, the integration of biochar with semiconductors, metal oxides, and other inorganic materials has emerged as a promising strategy for the development of multifunctional composites with combined adsorptive and catalytic properties (Arumugam and Dhandapani 2025; El-Sabban *et al.* 2025).

Heterogeneous photocatalysis has been extensively investigated as an advanced oxidation process capable of degrading persistent organic pollutants in water and industrial effluents (Chong *et al.* 2010). In this process, semiconductors such as TiO_2 are activated by light irradiation, generating electron–hole pairs that react with water and dissolved oxygen to produce reactive oxygen species, such as hydroxyl radicals, which are highly effective in degrading organic contaminants (Hashimoto *et al.* 2005; CARP 2004).

Despite its advantages, TiO_2 presents important limitations, including the rapid recombination of electron–hole pairs and limited absorption in the visible light region, as it is predominantly activated under ultraviolet radiation.

To overcome these limitations, several strategies have been proposed, including doping with metals or non-metals, the formation of heterostructures, and immobilization on carbon-based supports (Bhakta *et al.* 2023).

Within this framework, the combination of biochar and TiO_2 has attracted increasing attention. Studies have shown that these composites exhibit enhanced performance in the degradation of organic pollutants due to improved charge separation, increased surface area, and facilitated electron transfer at the interface between materials (Chandra *et al.* 2021).

The presence of biochar as a support enhances semiconductor dispersion and promotes the generation of reactive oxygen species, resulting in improved efficiency in the treatment of contaminated aqueous systems.

In recent years, the number of studies on biochar/TiO_2 composites has increased significantly, reflecting growing scientific interest in environmental remediation and agro-industrial waste valorization. Previous bibliometric studies have primarily focused on biochar production, agricultural waste valorization, modified biochar materials, photocatalytic systems, or TiO_2-based environmental applications as separate research topics. However, studies integrating these themes into a single bibliometric framework, particularly emphasizing sugarcane-derived biochar, TiO_2-based hybrid materials, and their environmental applications, remain limited. By examining these interconnected topics within a single bibliographic dataset, the present study provides an integrated perspective on the scientific development of this interdisciplinary research field and highlights relationships that are not readily captured when these themes are analyzed separately (Donthu *et al.* 2021; White and McCain 1998).

Based on this context, the present study aimed to perform a bibliometric mapping of the scientific literature on sugarcane residue-derived biochar associated with titanium dioxide (TiO_2) for environmental applications. The analysis focused on publication trends, geographical distribution of scientific production, international collaboration patterns, and the thematic structure identified through keyword co-occurrence analysis. By integrating these different analytical dimensions, this study provides a comprehensive overview of the evolution of the field, identifies major research trends, and highlights knowledge gaps that may guide future investigations.

2. Methodology

This study was conducted through a bibliometric analysis and scientific mapping of the literature. By using quantitative indicators, this approach allows for the investigation of publication trends, emerging research topics, and patterns of collaboration over time (Skute *et al.* 2019).

Bibliographic data were collected from the Scopus and Web of Science Core Collection (WoS) databases. The records were retrieved on March 18, 2026. The period analyzed spanned the years 2014 through 2025, as this represents the phase during which research related to the valorization of sugarcane waste for biochar production and its environmental applications began to show continuous growth and a sufficient volume of publications to support consistent bibliometric analyses. Furthermore, this time frame was considered sufficiently broad to identify trends in the growth of scientific output, patterns of collaboration, and the thematic evolution of the field. The year 2026 was excluded because indexing was still incomplete at the time of data collection.

The search was limited to English-language publications, as English is the predominant language of international scientific communication and provides greater standardization of the metadata available in the databases consulted, thereby facilitating the reproducibility of the analysis. However, we acknowledge that this choice may introduce a language bias, since studies published in other languages were not considered.

Regarding document type, only original scientific articles and papers published in conference proceedings were included, as they represent original scientific contributions widely used in bibliometric analyses, allowing for the evaluation of both well-established research and recently published scientific advances. Editorials, short notes, book chapters, and review articles were excluded in order to focus the analysis on primary scientific output and avoid distortions in bibliometric indicators resulting from the high number of citations typically accumulated by review articles.

It should be noted that this restriction applies exclusively to the bibliographic corpus used in the quantitative bibliometric analyses. Review articles, systematic reviews, and other literature synthesis studies continued to be used as references for theoretical grounding, contextualization of the topic, and discussion of the results; however, they were not included in the database used for the bibliometric analyses.

The methodological workflow used for data retrieval, filter application, database integration, duplicate removal, and construction of the final bibliographic corpus is shown in Figure 1.

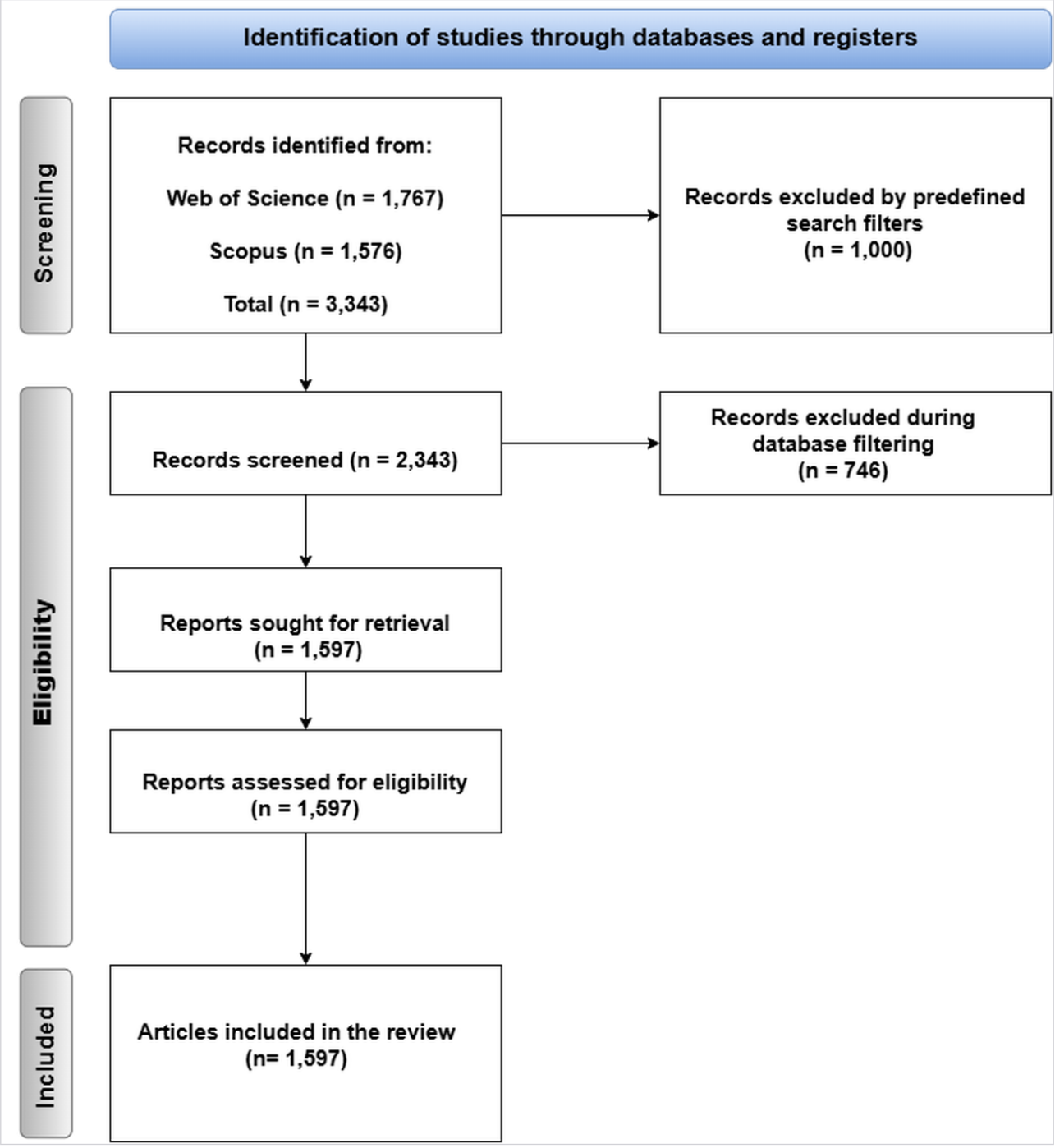

Figure 1. Illustrates the workflow used for database searching, application of predefined search filters, integration of records from Scopus and Web of Science, duplicate removal, and construction of the final bibliographic dataset used for bibliometric analyses.

The complete operational search strategy carried out on both platforms is detailed in Table 1. Due to differences in syntax between the databases, equivalent queries adapted to the respective search fields (TS for Web of Science and TITLE-ABS-KEY for Scopus) were used, while preserving the same logical structure based on Boolean operators, grouping with parentheses, and the use of quotation marks for compound expressions.

Table 1. Search strategy applied in Scopus and Web of Science databases.

Database	Search Field	Search Terms	Filters
Scopus	TITLE-ABS-KEY	Field 1: ("biochar" OR "titanium dioxide" OR "TiO_2") AND Field 2: ("sugarcane" OR "sugar cane" OR "bagasse" OR "sugarcane bagasse")	Language: English Period: 2014–2025 Document types: Articles and conference papers
Web of Science	TOPIC	Field 1: ("biochar" OR "titanium dioxide" OR "TiO_2") AND Field 2: ("sugarcane" OR "sugar cane" OR "bagasse" OR "sugarcane bagasse")	Language: English Period: 2014–2025 Document types: Articles and conference papers

The bibliometric analysis included descriptive and relational indicators. The descriptive analysis covered annual scientific output, document types, and the distribution of sources. The relational analysis examined productivity by authors, countries, and institutions, as well as collaboration networks and co-authorship patterns (Noyons *et al.* 1999). After removing duplicates, the consolidated dataset constituted the bibliographic corpus used in the bibliometric analyses. Research articles and conference-related publications (including proceedings) were included, while other types of documents, such as editorials, notes, and review articles, were excluded to maintain the analytical focus on primary scientific contributions. The final dataset comprised publications that met all inclusion criteria and were deemed suitable for bibliometric analysis.

The metadata on authors and institutional affiliations were preserved as provided by the Scopus and Web of Science databases. Data processing involved integrating the records and removing duplicates to construct the bibliographic corpus, without performing additional procedures for author disambiguation or manual harmonization of institutional affiliations. Consequently, the institutional and authorship analyses reflect how these entities are indexed in the databases consulted.

The search was structured to comprehensively capture both integrated studies and independent research in the relevant technological fields, focusing on biochar, titanium dioxide, and sugarcane-derived waste. This approach ensured the inclusion of studies addressing both individual and combined applications of these materials, providing a representative dataset for analysis (Caputo and Kargina 2022).

After the data was retrieved, the records were exported in a standardized format and processed in the RStudio environment using the Bibliometrix package and its graphical interface, Biblioshiny. Data preprocessing included standardizing authors, affiliations, and keywords, as well as manually correcting inconsistencies to ensure data reliability. The combined use of Bibliometrix/Biblioshiny and bibliometric visualization tools is widely recommended due to their analytical flexibility and ability to process large datasets from multiple sources, enabling the construction of co-authorship networks, thematic maps, and conceptual frameworks (Cabral *et al.* 2025).

2.1. Database Integration and Deduplication Pipeline

The records retrieved from the Web of Science Core Collection were exported in plain text format using the "Full Record and Cited References" option. Due to the platform's export limit, the records

were divided into three files. The records from Scopus were exported in CSV format, containing the available bibliographic metadata. The citation counts used in the bibliometric analyses were obtained directly from the metadata provided by the respective databases. After consolidating the Web of Science files, the records were merged with those from Scopus, forming a single dataset for the subsequent stages of deduplication and analysis.

The keyword co-occurrence networks were generated using VOSviewer version 1.6.20. The bibliometric analyses were performed using R version 4.5.0, RStudio version 2026.01.1+403, and the Bibliometrix package (version 5.0.1) through its Biblioshiny interface. The exported files were converted using the convert2df() function, with the parameters dbsource = “wos” and format = “plaintext” for Web of Science records, and dbsource = ‘scopus’ and format = “csv” for Scopus records. The files from Web of Science were initially consolidated into a single dataset and subsequently integrated with the Scopus records. The VOSviewer analysis was performed using the "Create a map based on bibliographic data" option, with the "All Keywords" field selected as the unit of analysis and the Full Counting method. A minimum occurrence threshold of 54 was adopted, resulting in 6,292 identified keywords, of which 20 met the inclusion criterion and were selected for network construction. No thesaurus file was used. Variations in spelling, abbreviations, singular/plural forms, and equivalent terms were standardized during the metadata cleaning stage prior to network construction. Unless otherwise specified, the default VOSviewer settings were adopted for normalization, clustering, and network layout (Aria and Cuccurullo 2017; van Eck and Waltman 2010; Moral-Muñoz *et al.* 2020).

Duplicate records were identified and removed using the `duplicatedMatching()` function, with the document title as the comparison field (Field = “TI”), approximate matching (exact = FALSE), and a minimum similarity threshold of 0.95 (tol = 0.95). This procedure made it possible to identify records with identical or highly similar titles, including minor differences in spelling, punctuation, and indexing between the two databases. No separate deduplication step based exclusively on DOI or the first author’s last name was employed. When records had titles similar enough to meet the established similarity criterion, only one record was retained in the consolidated dataset.

After integration and deduplication, the metadata was verified to minimize any remaining inconsistencies. Author and institutional names were standardized when necessary, reducing ambiguities arising from spelling variations and differences in indexing across databases. When discrepancies were identified between metadata from Scopus and Web of Science, the record considered most complete was retained for subsequent analyses.

After integrating the databases, the metadata was standardized to reduce obvious inconsistencies between records from Scopus and Web of Science. This process included correcting spelling variations, obvious duplicates, and minor differences in the spelling of institution and author names, while preserving, whenever possible, the original nomenclature provided by the indexing databases. Neither an external institutional thesaurus nor a specific dictionary was used for complete entity disambiguation. Thus, organizations indexed as university systems, national scientific information platforms, or other aggregated entities remained as recorded in the databases when it was not possible to unequivocally establish their correspondence with individual institutions. Similarly, the identification of authors was based on the standardized metadata provided by the databases; no complete manual disambiguation was performed for authors with identical last names and initials.

Since this study consists of a bibliometric analysis based exclusively on bibliographic metadata, no manual screening of titles, abstracts, or full-text articles was performed. Figure 1 depicts only the process of data retrieval, application of filters, database integration, removal of duplicates, and preparation of the dataset; it does not correspond to the eligibility flowchart of a systematic review.

After completing all stages of retrieval, integration, deduplication, and standardization of the metadata, the final bibliographic corpus consisted of 1,597 unique publications, forming the database used in all bibliometric and scientific mapping analyses conducted in this study.

3. Results and discussion

3.1. Annual Scientific Production

The evolution of scientific output over the analyzed period is shown in Figure 2. The bibliometric survey identified a total of 1,597 documents published between 2014 and 2025, distributed across 538 sources, including peer-reviewed journals and conference proceedings.

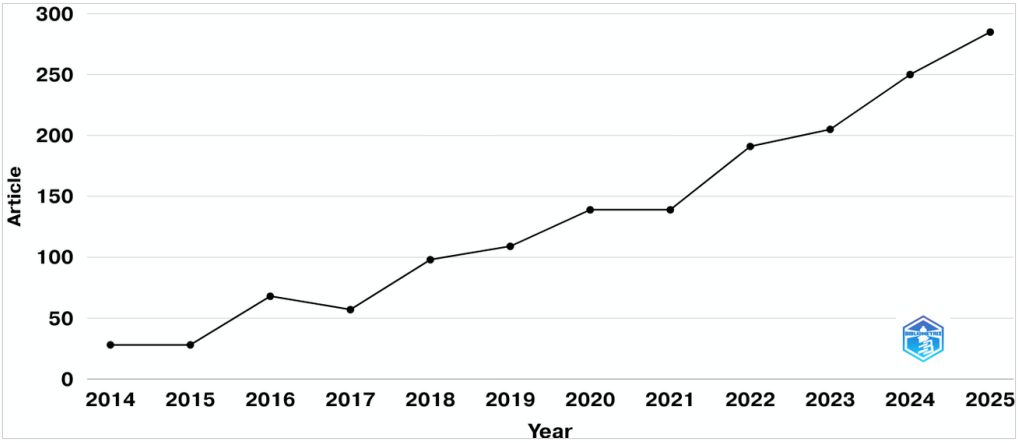

Figure 2. Annual Scientific Production.

There is a general upward trend in annual scientific output, highlighting the growing interest in the valorization of lignocellulosic waste and the development of sustainable materials for environmental remediation (Fang *et al.* 2020; Meirelles *et al.* 2025). Despite some fluctuations over the period, such as a decline between 2020 and 2021, the overall trend indicates a substantial expansion of research activity.

Starting in 2022, a sharp increase in the number of publications is evident, reaching its peak in 2025. This trend reflects intensified global research efforts focused on biochar-based materials and TiO_2 applications, particularly in adsorption and photocatalysis processes for contaminant removal (Ahmad *et al.* 2014).

Table 2. Main Information.

Description	Results
Timespan	2014-2025
Sources (Journals, Books, etc)	528
Documents	1597
Annual Growth Rate %	23.48
Document Average Age	4.43
Average citations per doc	28.39
References	82585
Keywords Plus (ID)	3830
Author's Keywords (DE)	3730
Authors	6250
Authors of single-authored docs	10
Single-authored docs	20
Co-Authors per Doc	5.62
International co-authorships %	28.55
Article	1,487
Article; book chapter	5

Table 2. (continued)

Description	Results
Article; data paper	1
Article; early access	6
Article; proceedings paper	13
Article; retracted publication	1
Conference paper	56
Proceedings paper	27
Proceedings paper; book chapter	1

The average of 28.39 citations per document was calculated based on the citation counts available in the Scopus and Web of Science metadata, which were consolidated into the integrated dataset. The average age of the publications was 4.43 years, indicating that the corpus consists predominantly of recent studies (Table 2).

In terms of document types, the bibliographic corpus consisted predominantly of original scientific articles (1,487 documents), supplemented by 110 conference papers (Table 2). This distribution highlights the predominance of results published in peer-reviewed journals, while conference papers represent a smaller, yet relevant, portion of the scientific output analyzed (Fang *et al.* 2020; Meirelles *et al.* 2025).

In terms of authorship structure, a total of 6,250 authors contributed to the dataset, with an average of 5.62 co-authors per paper, reflecting a high level of collaboration. Furthermore, approximately 28.55% of the publications involve international co-authorship, highlighting the global and interdisciplinary nature of the research field (Table 2).

Overall, the results demonstrate that research on biochar and TiO_2-based composites has expanded significantly, driven by the growing demand for sustainable technologies aimed at environmental remediation, waste valorization, and the development of advanced materials.

3.2. Geographic Distribution of Scientific Production

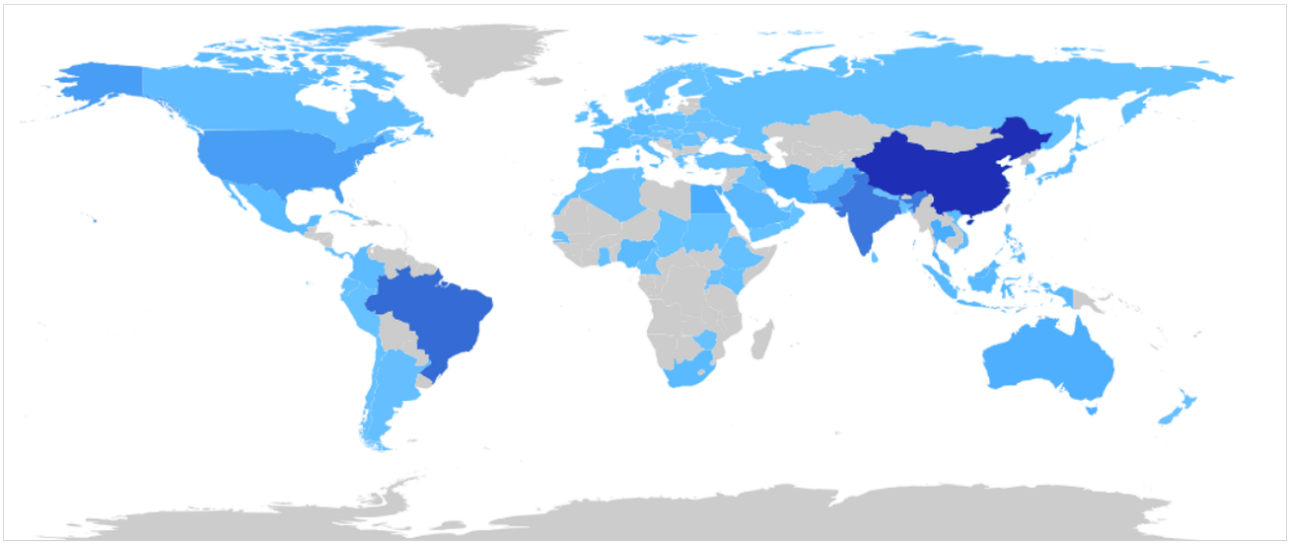

Figure 3. Scientific production by country. World map showing the geographical distribution of scientific production. The color intensity represents the number of publications associated with each country, with darker blue indicating higher publication counts and lighter blue indicating lower publication counts. Gray indicates countries with no records in the analyzed dataset.

The observed geographic distribution (Figure 3) may be related to factors such as existing scientific capacity, national research priorities, available infrastructure, and interest in technologies aimed at utilizing lignocellulosic waste (Silalertruksa *et al.* 2022; Pereira *et al.* 2025). However, since this study was exclusively bibliometric in nature, indicators of agricultural production, biomass availability, investments in research and development, or scientific funding were not analyzed. Thus, any association between these factors and scientific productivity should be interpreted only as a plausible hypothesis, not as an established causal relationship.

Table 3. Top 10 countries according to corresponding-author country, including Single Country Publications (SCP) and Multiple Country Publications (MCP).

Country	Publications	Share of publications (%)	SCP	MCP	MCP ratio (%)
China	359	22.5	257	102	28.4
India	259	16.2	216	43	16.6
Brazil	234	14.7	185	49	20.9
Pakistan	70	4.4	28	42	60.0
United States	68	4.3	42	26	38.2
Iran	65	4.1	59	6	9.2
Thailand	54	3.4	43	11	20.4
Egypt	48	3.0	36	12	25.0
Australia	40	2.5	20	20	50.0
Indonesia	39	2.4	34	5	12.8

Note: SCP = Single Country Publications; MCP = Multiple Country Publications; MCP Ratio = MCP/Documents × 100. The indicators were generated by the Bibliometrix package based on the corresponding author's country.

Figure 4 shows the geographic distribution of scientific output, while Table 3 summarizes the ten countries with the highest number of documents and their respective indicators of international collaboration. The results were obtained based on the country of affiliation of the corresponding author, according to the indicators generated by the Bibliometrix software package (Aria and Cuccurullo 2017). The Single Country Publications (SCP) indicator represents documents whose authors belong exclusively to a single country, while Multiple Country Publications (MCP) corresponds to documents produced in collaboration between authors from different countries (Sweileh *et al.* 2016). Thus, the values presented represent the classification based on the corresponding author's country and not a complete count of all national affiliations present in each document.

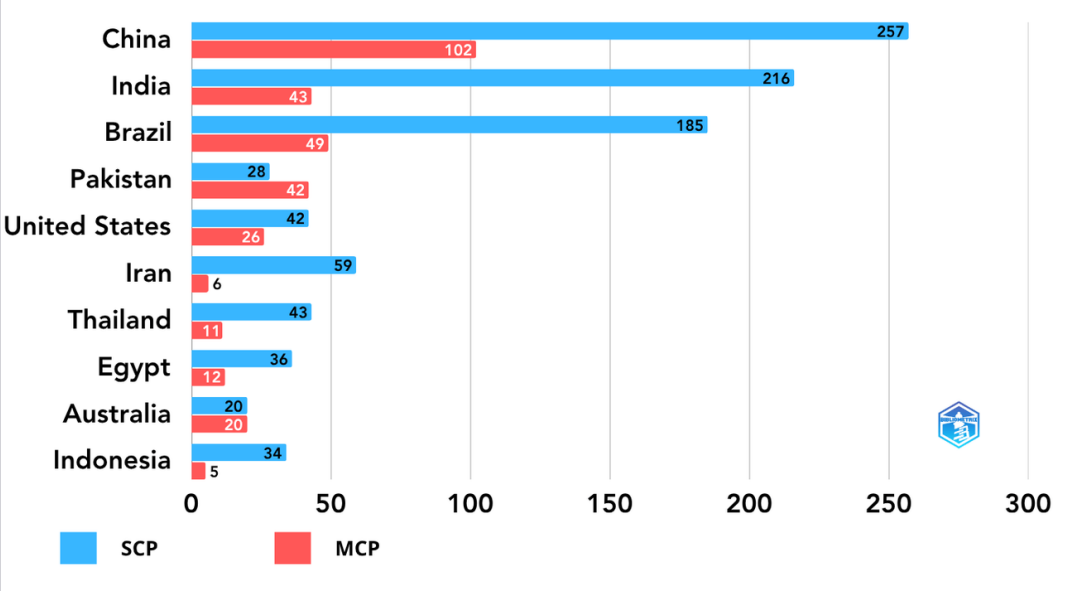

Figure 4. Scientific Production by Country: SCP and MCP.

China led in scientific output, with 359 publications (22.5%), followed by India, with 259 publications (16.2%), and Brazil, with 234 publications (14.7%). Together, these three countries accounted for more than half of the publications in the analyzed corpus, highlighting their prominent role in research related to biochar production from sugarcane waste and its environmental applications (Lyu *et al.* 2018; Domingues *et al.* 2020).

Indicators of international collaboration revealed significant differences among countries. China produced 257 domestically authored publications (SCP) and 102 publications involving international collaboration (MCP), demonstrating high scientific productivity combined with significant participation in international research networks. India (216 SCP and 43 MCP) and Brazil (185 SCP and 49 MCP) also recorded high numbers of publications, though with a predominance of studies conducted at the national level. In contrast, countries such as Pakistan (60.0% MCP) and Australia (50.0% MCP) showed higher proportions of international collaboration relative to their total scientific output, indicating greater integration into global research networks.

These results show that a higher number of publications does not necessarily imply greater internationalization of scientific research. While some countries focus their research output on domestic collaborations, others have a higher relative share of research conducted through international cooperation, highlighting different strategies for scientific collaboration.

These findings indicate that a high volume of publications does not necessarily correspond to greater international collaboration. While China, India, and Brazil dominate total output, countries such as Pakistan and Australia show greater integration into global research networks.

The predominance of SCP among leading countries suggests that a large portion of research is still conducted within national frameworks. However, the substantial presence of MCP highlights the growing internationalization of the field and the importance of collaboration among countries for advancing research on biochar and TiO_2-based materials (Shi *et al.* 2022; El-Sabban *et al.* 2025).

Overall, the results show that scientific output in this field is geographically concentrated and increasingly interconnected, reflecting the combined influence of resource availability, scientific capacity, and global collaboration in addressing environmental challenges and developing sustainable technologies.

3.3. Institutions and Collaboration Networks

The institutional analysis (Figure 5) reveals that scientific output is concentrated in a limited number of universities and research systems, highlighting the central role of key organizations in advancing this field of research. Among the institutional entities recorded in the databases consulted, the Egyptian Knowledge Bank had the highest number of associated documents. This result should be interpreted with caution, as it reflects how affiliations are indexed in bibliographic databases and may include national information platforms or aggregated institutional systems, followed by Guangxi University and the Indian Institute of Technology (IIT System). Other relevant collaborators include the University of Agriculture Faisalabad, the State University System of Florida, the University of Florida, and the Chinese Academy of Sciences (Chen *et al.* 2023).

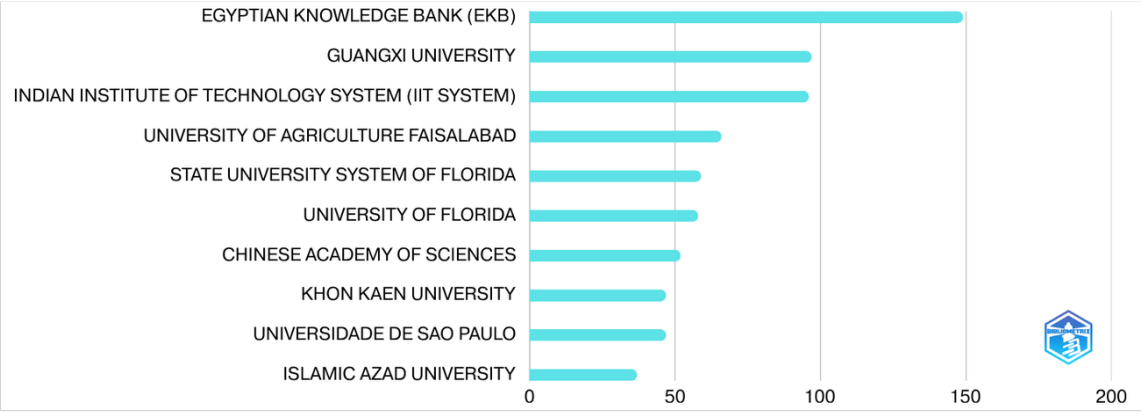

Figure 5. Scientific Production by Institution.

These results indicate a strong geographic alignment between leading institutions and countries with high scientific output, particularly in Asia and the Middle East. Institutions in India, China, Pakistan, and Egypt play a prominent role, reflecting growing investment in research related to environmental technologies, biomass utilization, and advanced materials (Chen *et al.* 2023).

The presence of institutions such as the University of São Paulo (USP) and Khon Kaen University further highlights the global distribution of research efforts, although their contribution is comparatively smaller than that of leading institutions (Schellekens *et al.* 2018; Kumalayanti *et al.* 2025). This suggests that, although scientific output is distributed globally, it remains concentrated in specific, high-output research systems.

From the perspective of collaboration, the structure of institutional networks reflects the patterns observed at the country level, with research predominantly conducted within well-established national frameworks (Shi *et al.* 2022; El-Sabban *et al.* 2025). This is particularly evident in countries with strong academic infrastructure, where institutions maintain high internal productivity while gradually expanding international collaboration.

In bibliometric studies, identifying institutional collaboration networks is essential for understanding how scientific knowledge is structured and disseminated among research groups, revealing patterns of cooperation and the organization of academic output. Overall, the findings indicate that research on biochar and TiO_2-based composites is driven by a core of highly productive institutions, located primarily in emerging and developing economies, where environmental challenges and resource availability stimulate scientific innovation (El-Sabban *et al.* 2025). Institutional networks have helped accelerate the development of sustainable technologies for environmental remediation and biomass utilization (Aria and Cuccurullo 2017).

3.4. Keyword Analysis and Thematic Trends

Figure 6 presents a treemap of the most frequent keywords identified in the bibliographic dataset. Only terms that met the minimum occurrence threshold established for the analysis were included in

the visualization. The percentages shown correspond to the relative frequency of each keyword compared to the total number of occurrences of the keywords displayed in the treemap, allowing for a comparison of their representativeness within the selected dataset (Aria and Cuccurullo 2017; Cobo *et al.* 2011).

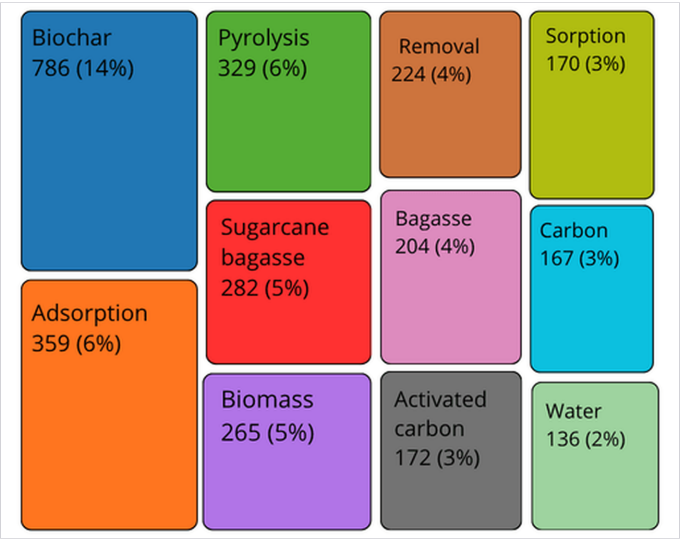

Figure 6. Treemap showing the most frequent author keywords identified in the analyzed corpus.

An analysis of keyword occurrence indicates that terms such as biochar, adsorption, pyrolysis, and sugarcane bagasse are among the most frequently reported in the literature, reflecting the strong focus on the production and application of biochar derived from lignocellulosic waste for environmental purposes (Arumugam and Dhandapani 2025; Shikuku and Jemutai-Kimosop 2020; Shi *et al.* 2022; Souza *et al.* 2025).

The prominence of these terms confirms that the thermochemical conversion of biomass via pyrolysis and its application in adsorption processes constitute the central focus of research in this field. This trend is consistent with recent studies highlighting the efficiency of biochar-based materials in removing pollutants, particularly in water and wastewater treatment systems (da Silva *et al.* 2025; Cai *et al.* 2025).

Furthermore, the presence of terms such as “activated carbon” (172 occurrences, 3%); “sorption” (170 occurrences, 3%); and “carbon” (167 occurrences, 3%) reinforces the relevance of carbonaceous materials in environmental remediation technologies. Terms such as “water” (136 occurrences, 2%) further highlight the environmental scope of the research, indicating applications in aquatic and terrestrial systems (Alharbi *et al.* 2025).

To explore the intellectual structure of the field, a three-field plot was constructed using the Bibliometrix package, as shown in Figure 7. The visualization relates authors (AU), keywords (DE), and scientific sources (SO), allowing us to identify the connections between these elements in the analyzed corpus. To facilitate interpretation, the plot was constructed using the eight authors with the highest number of publications, the eight most frequent keywords, and the eight most represented journals. The width of the connections is proportional to the number of documents shared between the connected elements, highlighting the strength of the relationships among authors, research topics, and publication outlets (Boyack and Klavans 2010; van Eck and Waltman 2010; Zupic 2015; Waltman *et al.* 2010).

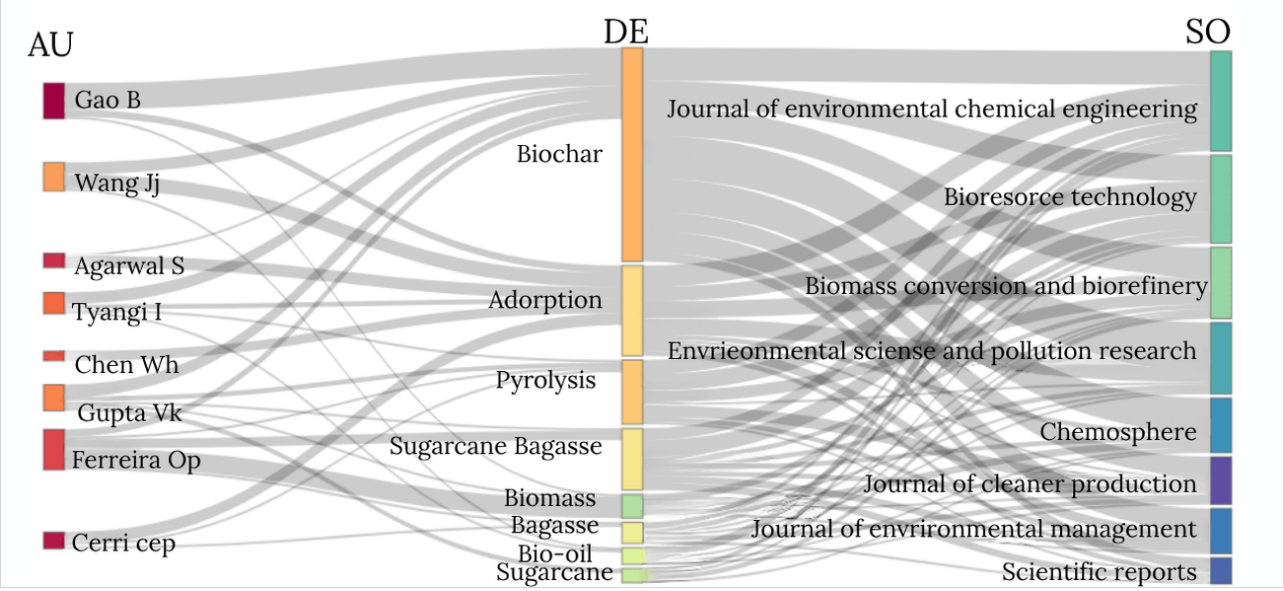

Figure 7. Three-field plot relating the eight most productive authors (AU), the eight most frequent author keywords (DE), and the eight most representative scientific sources/journals (SO) in the analyzed corpus. The width of the connections is proportional to the number of shared documents between the connected elements.

The central column highlights the most frequent keywords, with biochar, adsorption, pyrolysis, and sugarcane bagasse occupying prominent positions, confirming their role as the main research topics. On the left side, authors with the highest number of publications in the corpus stand out, such as Gao B, Wang Jj, and Agarwal S, who are associated with these topics. On the right side, the journals most represented in the dataset are shown, such as the "Journal of Environmental Chemical Engineering", "Bioresource Technology", and "Biomass Conversion and Biorefinery", highlighting the main publication outlets in the field (Yao *et al.* 2018; Luo *et al.* 2023).

To complement the analysis of keyword frequency, co-occurrence networks were generated using the VOSviewer software, as shown in Figure 8 (a–b). The cluster map in Figure 8(a) was used to identify conceptual relationships among the most frequently occurring keywords, while the overlay map in Figure 8(b) represents the average year of publication associated with each term, allowing for the identification of temporal trends in the evolution of the literature (Fang *et al.* 2020; Khare *et al.* 2021). It should be noted that warmer shades indicate keywords related to more recent publications and should not be interpreted, in isolation, as evidence of greater scientific relevance.

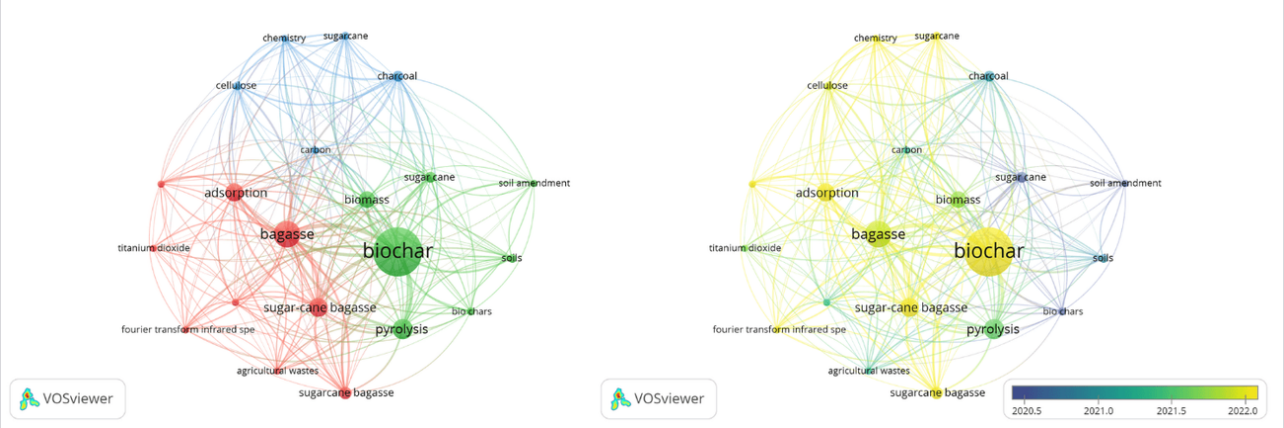

Figure 8. Keyword co-occurrence network generated using VOSviewer: (a) cluster map, in which node colors represent thematic clusters of related keywords; (b) temporal overlay map, in which node colors represent the average publication year of the documents associated with each keyword. The color scale ranges from earlier average publication years (blue) to more recent average publication years (yellow). The overlay reflects temporal evolution and should not be interpreted as an indicator of scientific relevance or impact.

Figure 8a (cluster map) reveals the organization of the field into interconnected thematic clusters. The term "biochar" occupies a central and highly connected position in the network, indicating its role as one of the main structuring elements of the research domain and its association with multiple topics under investigation (Loc 2023; Bhakta *et al.* 2023).

One prominent cluster is associated with *bagasse*, which shows strong connections to adsorption and titanium dioxide. This configuration points to a line of research related to the development of hybrid materials based on biochar and TiO_2 for adsorption and photocatalysis processes (Leichtweis *et al.* 2021; Tohamy *et al.* 2023). The observed connections highlight the thematic association between these terms in the analyzed literature, indicating an expanding research topic; however, this alone does not allow us to infer its degree of scientific consolidation.

Another relevant cluster includes terms such as *pyrolysis*, *biomass*, and *soil amendment*, which are associated with the production, characterization, and environmental application of biochar derived from agricultural waste. This cluster reflects the fundamental processes underlying biochar generation and its use in both environmental remediation and agricultural improvement (Borges *et al.* 2020; Barragán-Mantilla *et al.* 2023).

Additionally, smaller clusters related to contaminant removal (e.g., dyes and heavy metals) and material characterization can be observed, indicating the diversification of research topics and the emergence of more specialized applications (Cai *et al.* 2025).

Figure 8b (temporal overlay map) illustrates the evolution of research topics over time. Terms represented in warmer shades are associated with more recent average publication years, indicating themes that have begun to appear more frequently in recent studies. In contrast, early research, represented by cooler colors, is more strongly associated with fundamental topics such as biomass, carbon, and pyrolysis processes, reflecting the early stages of knowledge development in the field (Ahmad *et al.* 2014).

Overall, a combined analysis of keyword frequency, structural relationships, and temporal trends demonstrates that the scientific literature is organized around three main research areas: (i) biochar production via pyrolysis, (ii) application in adsorption processes for contaminant removal, and (iii) development of functional and hybrid materials for environmental remediation. Furthermore, the growing emphasis on biochar/TiO_2 hybrid systems highlights increasing technological sophistication (Ahmad *et al.* 2014; Afshar and Mofatteh 2024).

3.5. Research Gaps and Future Perspectives

Although the literature reviewed demonstrates significant growth and increasing thematic diversification, the bibliometric results reveal the persistence of major research gaps related to the valorization of sugarcane waste for biochar production and its integration with functional materials. Recent studies have highlighted the potential of these materials for environmental applications, particularly in the treatment of water and contaminated effluents (Inyang *et al.* 2015; Park *et al.* 2019).

One of the main gaps identified relates to the still-limited integration between research focused on biochar production via pyrolysis and that dedicated to the development of advanced composites with photocatalytic properties, particularly those involving TiO_2. Although terms related to adsorption and effluent treatment are consistently present in the co-occurrence network, the term "titanium dioxide" was also identified among the analyzed topics, indicating its application in studies focused on the development of hybrid materials for environmental applications (Cañon-Tafur *et al.* 2025; Chauhan *et al.* 2025; Chen and Mao 2007). However, its frequency of occurrence is lower than that observed for the main themes in the field, suggesting that this line of research is still in the process of expansion and development.

Another important aspect concerns the understanding of the synergistic mechanisms between adsorption and photocatalysis. In biochar/TiO_2 composites, biochar can act simultaneously as a structural support, an adsorbent, and an electron transfer mediator, reducing the recombination of electron-hole pairs generated during the photocatalytic process. This combined effect has been identified as one of the factors contributing to increased efficiency in the degradation of organic pollutants in aqueous environments (Du et al., 2024; Azizah et al., 2025).

However, although adsorption and photocatalysis are often used in a complementary manner in biochar/TiO_2 composites, these processes have distinct mechanisms and should not be considered equivalent. While adsorption facilitates the transfer of the contaminant from the aqueous phase to the material's surface, photocatalysis promotes its chemical transformation through the action of reactive species. Furthermore, the degradation of the original contaminant does not necessarily imply its complete mineralization or a reduction in toxicity, since intermediate products may form during the process. In this context, future studies should consider, in addition to removal efficiency, aspects such as mineralization, byproduct formation, ecotoxicity, biochar regeneration, catalyst recovery, stability over successive cycles of use, potential leaching of metals or nanoparticles, and the assessment of the environmental safety of these materials in real-world applications (Chandra *et al.* 2021; Chong *et al.* 2010).

Furthermore, the growing interest in using lignocellulosic waste as a feedstock for biochar production underscores the potential of these materials as an alternative for the valorization of agroindustrial waste within the context of the circular economy and environmental sustainability. The valorization of agricultural and agroindustrial waste enables the production of low-cost adsorbents and contributes to circular economy strategies and sustainable waste management (Verma *et al.* 2024). In this context, biochar has been extensively investigated as a promising material for the removal of emerging pollutants in aquatic environments, due to its high surface area, the presence of functional groups, and significant adsorption capacity (Dong *et al.* 2023; Arfasa and Tilahun 2025).

Although biochar is often associated with sustainability and circular economy strategies, its environmental performance depends on various factors throughout its life cycle, and not exclusively on the use of agricultural waste as a raw material. Factors such as carbon yield, material stability, energy demand for pyrolysis, emissions associated with composite synthesis, TiO_2 production, material regeneration, and end-of-life disposal can significantly influence its environmental footprint. Therefore, future studies should integrate life cycle assessments (LCA), techno-economic analyses, and carbon balances to quantify the potential environmental benefits and possible trade-offs between remediation efficiency and process-related impacts (Alighanbari *et al.* 2025; Arfasa and Tilahun 2025; Fawzy *et al.* 2022; Li *et al.* 2024). From an institutional and geographic perspective,

although the field is experiencing strong growth in countries such as China, Brazil, and India, the results also point to the need to strengthen international and inter-institutional collaborations, particularly around integrated approaches involving materials science, environmental engineering, and the circular economy. The predominance of publications classified as Single-Country Publications (SCP) suggests that there is still room to expand the internationalization of research and strengthen cooperation networks focused on methodological standardization, comparisons between different raw materials, and the development of more robust protocols for performance evaluation. This trend has also been observed in recent bibliometric studies on heavy metal adsorption, environmental applications of biochar, modification of biochars for aquatic remediation, carbon sequestration, and biochar life-cycle assessment (Admas *et al.* 2026).

Looking ahead, the results suggest potential for expanding research related to the development of biochar/TiO_2 composites, the surface modification of biochars, the use of semiconductor dopants, and the application of these materials in the removal of emerging contaminants from complex environmental matrices. Promising directions also include the integrated valorization of agro-industrial waste within the context of the circular bioeconomy, the development of multifunctional materials with greater selectivity and stability, and the incorporation of environmental, economic, and technological assessment tools capable of supporting the transfer of these technologies to full-scale applications (Al-Gailani *et al.* 2025; Badawi *et al.* 2026).

These findings are consistent with recent review studies that address biochar- and metal oxide-based nanocomposites, surface-modified TiO_2 photocatalysts, the mineralization of emerging contaminants via advanced oxidative processes (AOPs), strategies for standardizing and scaling up these processes, and aspects related to the energy consumption of photocatalytic materials used in environmental remediation (Aziz *et al.* 2025; Dhila *et al.* 2025).

3.6. Study Limitations

This study has some limitations related to the quality and standardization of the metadata provided by the bibliographic databases. Although a basic harmonization of institutional affiliations and authors' names was performed to reduce obvious inconsistencies, some aggregated entities, such as university systems, national scientific information platforms, and other organizations indexed by the databases, were retained as they appeared in the original records. Furthermore, authors identified only by last name and initials may represent different researchers, a limitation inherent in bibliometric analyses based on metadata. Thus, institutional and author productivity indicators should be interpreted with these limitations in mind (Mongeon and Paul-Hus, 2014; Nowakowska, 2025).

Another limitation relates to citation lag, especially for the most recent publications included in the analysis period (2024–2025), which have not yet had sufficient time to accumulate citations. Furthermore, bibliographic databases are continuously updated, so that new indexings, metadata corrections, and changes to records may result in minor differences if the search strategy is replicated at a later time (Belter 2015).

Although a basic harmonization of author names, institutions, and keywords was performed to reduce obvious inconsistencies, ambiguities arising from different author signature formats, institutional variations, and the lack of complete standardization of descriptors may influence some bibliometric indicators, particularly those related to institutional productivity, scientific collaboration, and co-occurrence networks. Since a formal thesaurus was not used, minor terminological variations may remain in the dataset (Tang and Walsh 2010).

The results also depend on the search strategy used. Although the search was designed to retrieve literature related to biochar derived from sugarcane waste, titanium dioxide, and environmental applications, minor changes in the combination of terms, Boolean operators, or inclusion criteria could yield a different set of documents a characteristic inherent to bibliometric studies (Dagli *et al.* 2025).

In addition, all analyses were conducted using the full-counting method, which is the default setting in Bibliometrix and VOSviewer. Thus, each document contributes in full to the authors, institutions, and countries involved, which may favor entities with a greater number of co-authors compared to approaches based on fractional counting (Perianes-Rodriguez *et al.* 2016).

Finally, it is important to note that bibliometric indicators reflect patterns of scientific output, collaboration, and academic impact, but do not, on their own, allow for an assessment of the technological performance of the materials studied or provide evidence of their environmental efficiency (Dagli *et al.* 2025). Aspects such as adsorption capacity, photocatalytic activity, stability, regeneration, economic viability, and environmental performance must be investigated through experimental studies, life-cycle assessments, and complementary techno-economic analyses (Fawzy *et al.* 2022).

4. Conclusions

This study stands out for integrating, within a single bibliographic corpus, research on biochar production, its environmental applications, TiO_2-based hybrid materials, and the valorization of sugarcane waste. This approach allowed us to identify not only individual research trends; the results of this bibliometric analysis highlight the continuous growth and increasing diversification of research related to the valorization of sugarcane waste for biochar production and the development of materials for environmental remediation. The expansion of scientific output, combined with the strengthening of scientific collaboration networks and the thematic diversification observed throughout the analyzed period, demonstrates the evolution of this field of research on an international scale.

The geographic analysis revealed a concentration of scientific output in countries with strong agroindustrial activity, particularly China, India, and Brazil, while collaboration indicators showed differences in patterns of international cooperation among the most productive countries. These results underscore the importance of expanding international collaborations to strengthen scientific and technological development in this field.

Keyword and co-occurrence network analyses made it possible to identify the main topics investigated and their evolution over time. It was observed that terms related to adsorption, pyrolysis, biomass, and biochar constitute the core themes of the literature, while topics involving hybrid materials based on biochar and TiO_2 are associated with more recent publications, indicating an expanding line of research.

Although this study provides a comprehensive overview of the evolution of the literature through descriptive bibliometric indicators, no advanced bibliometric analyses were conducted, such as co-citation, bibliographic coupling, thematic maps, thematic evolution, collaboration networks among authors and institutions, or centrality indicators. These approaches can complement our understanding of the intellectual structure and dynamics of the scientific field and are recommended for future studies.

Compared to previous bibliometric studies, which predominantly addressed biochar production and modification, agricultural waste recovery, photocatalytic systems, and TiO_2-based environmental applications separately, the main contribution of this study lies in the integration of these different areas into a single bibliometric overview, with an emphasis on sugarcane waste. This approach highlighted not only the predominance of well-established topics, such as pyrolysis and adsorption, but also an emerging convergence between the valorization of agro-industrial residues, carbonaceous materials, and TiO_2-based photocatalytic systems. Thus, the study helps define the current structure of this interdisciplinary field and identifies the integration of biochar and TiO_2 as an expanding research frontier, still marked by gaps related to performance evaluation, stability, environmental safety, and the feasibility of large-scale application.

Declarations

Author contributions. Carlos Henrique Tenório de Lima: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – Original Draft, and Writing – Review & Editing. Giane Gonçalves Lenzi: Methodology, Formal analysis, and Writing – Review & Editing. Maria Eduarda Kounaris Fuziki: Data curation, Visualization, and Writing – Review & Editing. Angelo M. Tusset: Formal analysis and Writing – Review & Editing. José Manoel Balthazar: Supervision and Writing – Review & Editing. Eduardo César Meurer: Supervision, Project administration, and Writing – Review & Editing. Leda Maria Saragiotto Colpini: Conceptualization, Supervision, Project administration, and Writing – Review & Editing. All authors have read and approved the final version of the manuscript.

Conflicts of 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.

Data availability. The raw data supporting the conclusions of this article will be made available by the authors on request.

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