Next Materials 12 (2026) 102051

Contents lists available at ScienceDirect

Next Materials

journal homepage: www.sciencedirect.com/journal/next-materials

Research article

Nano-biochar research: A scopus-based bibliometric analysis of the 2016–2025 period

Kingsley O. Iwuozor [a,*], Hussein Kehinde Okoro [a], Adewale George Adeniyi [b]

[a] Department of Industrial Chemistry, Faculty of Physical Sciences, University of Ilorin, PMB 1515, Ilorin, Nigeria
[b] Department of Chemical Engineering, University of Ilorin, PMB 1515, Ilorin, Nigeria

ARTICLE INFO

Keywords:
Biochar modification
Environmental sustainability
Green chemistry
Material synthesis
Water treatment

ABSTRACT

Nano-biochar has emerged as a promising material for environmental remediation, sustainable agriculture, and advanced material applications. Despite its growing importance, an understanding of research trends, leading contributors, and thematic evolution remains limited. This study performs a bibliometric analysis of nano-biochar research using the Scopus database, covering the period 2016–2025 and encompassing 261 peer-reviewed documents published in English. The analysis is based on data from a single database and is therefore representative of Scopus-indexed literature. The analysis shows rapid publication growth, from a single publication in 2016–75 in 2025, accompanied by an increase in annual citations, reaching 2746 in 2025, showing the field's expanding influence and cross-disciplinary relevance. Research output is concentrated in key journals such as Science of the Total Environment, Journal of Cleaner Production, and Environmental Science: Nano, with the National Natural Science Foundation of China being the most prolific funding agency. Keyword co-occurrence and clustering analysis identify six thematic clusters: adsorption-based water treatment, biological interactions and environmental fate, sustainable agriculture, material synthesis and properties, heavy metal remediation, and surface charge characterization. Environmental science is the dominant subject area, followed by chemical engineering, chemistry, and agricultural and biological sciences. The findings indicate a maturation of the field, marked by a shift from foundational material characterization toward performance-driven applications, predictive modelling, and sustainability-focused research. This study provides a structured foundation for guiding future research efforts toward standardization, scalable synthesis, and responsible large-scale implementation of nano-biochar technologies.

1. Introduction

Biochar is a carbon-rich material formed through the thermochemical conversion of biomass under oxygen-limited conditions [1–3]. Its use as a soil amendment dates back thousands of years to the creation of the highly fertile Amazonian "terra preta" soils by pre-Columbian communities through the deliberate incorporation of charred organic residues [4,5]. In contemporary scientific and industrial contexts, biochar has become a focus of multidisciplinary research owing to its stability, porosity, and high surface reactivity [6]. Derived from diverse biomass feedstocks such as agricultural residues, forestry wastes, animal manure, and municipal organics, biochar is commonly produced through slow or fast pyrolysis, gasification, torrefaction, or hydrothermal carbonization [7]. The structure of biochar typically contains condensed aromatic rings, a high degree of carbonization, and surface functional groups including hydroxyl, carboxyl, and carbonyl moieties that enable strong adsorption and ion exchange [8]. These properties support its use in carbon sequestration, soil amendment, wastewater treatment, energy storage, and catalysis [9]. Consequently, biochar research has evolved beyond its traditional agricultural role, extending into materials science, environmental engineering, and renewable energy systems, showing a global shift toward sustainable and circular resource management.

Nano-biochar has emerged as an advanced generation of biochar designed to exploit nanoscale phenomena for improved performance [10]. Produced by further processing or synthesizing biochar into nanometre-sized particles, nano-biochar displays improved physicochemical and catalytic behaviour compared with bulk biochar [11,12]. The reduction in particle size leads to an increase in specific surface area and pore connectivity and a higher density of reactive sites that

* Corresponding author.
E-mail addresses: 21-68zn007.pg@students.unilorin.edu.ng (K.O. Iwuozor), okoro.hk@unilorin.edu.ng (H.K. Okoro).

https://doi.org/10.1016/j.nxmate.2026.102051
Received 13 January 2026; Received in revised form 24 March 2026; Accepted 30 March 2026
Available online 10 April 2026

strengthen adsorption and catalysis processes [13]. These properties enable improved removal of heavy metals, organic pollutants, and nutrients from aqueous and soil systems. Nano-biochar also improves redox reactions and serves as an efficient support for metal and enzyme immobilization in catalytic and bioremediation applications [14,15]. In agricultural systems, its interaction with soil colloids and microorganisms promotes nutrient availability, plant growth, and soil structure stability. Its small particle size facilitates better dispersion, ensuring uniform distribution within treated media [16]. Furthermore, nano-biochar exhibits improved electrochemical conductivity and tunable surface charge, expanding its potential in sensors, batteries, and supercapacitors [17]. Its high reactivity, stability, and tunable surface properties make it an important material for developing next-generation sustainable technologies in various applications. Therefore, understanding the research trends surrounding nano-biochar is essential for directing future investigations and optimizing its potential impact.

Bibliometric analysis provides a systematic and quantitative approach to examining patterns in scientific literature, including publication output, citation performance, co-authorship networks, and thematic evolution [18,19]. In the current research era marked by data-driven decision-making, bibliometric methods serve as essential tools for evaluating progress within scientific domains and identifying influential contributors, institutions, and emerging research themes [20,21]. Such analyses are particularly relevant in rapidly expanding fields like nano-biochar research, where publications have increased significantly over the past decade. Recent bibliometric studies have successfully mapped research areas in adjacent fields, including contaminant removal using cyclodextrin-based adsorbents, chitosan-based materials for emerging contaminants, and the fate of per- and polyfluoroalkyl substances in drinking water, demonstrating the value of such approaches for identifying knowledge gaps and guiding research priorities [22–24].

Several studies have attempted to apply bibliometric approaches to biochar-related topics. Wu et al. [25] conducted a bibliometric review of global biochar research published up to 2021, identifying hotspots in biochar production, characterization, and environmental applications. Their study, while informative, focused largely on general biochar trends without distinguishing nanoscale developments. Similarly, Zeng et al. [26], using bibliometric analysis, analyzed literature on ball-milled nano-sized biochar, emphasizing preparation methods, characterization, and environmental performance. Although valuable, their study was narrow in scope and did not explore nano-biochar produced through other techniques apart from ball-milling. Chaubey et al. [17] performed a bibliometric review on nano-biochar using the Web of Science database, providing foundational insights into publication growth. However, their analysis was limited by its temporal coverage, which predates the most prolific period of nano-biochar research (2023–2025), and its reliance on a single database, which may have underrepresented regionally focused or multidisciplinary studies. To address these limitations and to complement existing work, the present study leverages the Scopus database, known for its broader journal coverage in emerging fields, to capture recent developments and to provide a more current and representative assessment. This approach aligns with methodological best practices in bibliometric analysis, where multi-database or complementary database studies are increasingly recognized for providing a more complete picture of a research field's intellectual structure [27,28].

The aim of this study is to perform a bibliometric analysis of nano-biochar research to evaluate publication growth, identify leading contributors, and examine emerging research themes. The study focuses exclusively on nanoscale biochar rather than conventional biochar, offering a specific and data-driven understanding of how research in this area has evolved. Its novelty lies in combining quantitative and visual analyses to map publication trends, country performance, collaboration networks, and keyword co-occurrence using the Scopus database. This approach provides wider coverage and deeper analytical precision compared with earlier studies based on the Web of Science. The study also introduces an integrated analytical framework that connects scientific productivity with intellectual structure. It assesses which institutions and countries have driven innovation, how researchers collaborate, and which keywords dominate emerging areas. This study provides insights that are critical for evidence-based decision-making in both research and policy. Its structured mapping approach also supports international collaboration, guiding how resources should be directed toward impactful outcomes. Through these contributions, the study strengthens understanding of the nano-biochar research structure. It clarifies where progress has been made and where focused research is required to accelerate sustainable applications in various systems.

2. Methodology

2.1. Data source and search strategy

The analysis used data from Scopus, accessed on March 18, 2026. Scopus was selected for this study because it provides comprehensive, high-quality, and peer-reviewed bibliographic data across multiple disciplines, making it suitable for accurate citation and trend analysis. [29,30]. A prior bibliometric analysis of nano-biochar research has been published using the Web of Science (WoS) database [17]. The present study therefore complements existing work by employing Scopus, enabling a comparative assessment of findings across the two major bibliometric databases. This comparison is valuable as Scopus offers broader journal coverage, particularly in emerging and interdisciplinary fields, while WoS provides more selective indexing. The database's structured indexing and wide disciplinary coverage ensured reliable retrieval of relevant publications while facilitating consistent and reproducible bibliometric analysis.

To ensure thematic focus on nano-biochar as the core material, a targeted Boolean search string was developed following an iterative process. The keywords were derived from an extensive review of publications in the field and refined through iterative testing to balance recall and precision. Preliminary searches using broader terms such as "biochar AND nanoparticle" and "biochar AND nanomaterial" were tested and found to retrieve a high proportion of false-positive results (e.g., studies where biochar served only as a passive support for metal nanoparticles without nanoscale characterization of the biochar itself). Conversely, restricting the search to "nanobiochar" alone was found to miss relevant studies using hyphenated or descriptive variants. The final search string was therefore constructed to capture the core terminology while minimizing irrelevant inclusions: (ALL (nano-biochar) OR TITLE-ABS-KEY (nanobiochar) OR (nanosized AND biochar)), restricted to the Article title, Abstract, and Keywords fields. This query was selected after testing multiple variations and assessing the relevance of the first 50 retrieved records to ensure that the final dataset would accurately represent the nano-biochar literature. The search was not repeated for stability testing, as the Scopus database provides a fixed snapshot at the time of retrieval, and any subsequent search would show updates to the database rather than methodological instability [31,32].

2.2. Data Screening, Selection, and Processing

The data retrieval and screening process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and methodological rigor [33]. The complete workflow is illustrated in Fig. 1. The initial search using the specified query string yielded 423 documents. Application of the year filter reduced the dataset to 389 documents to capture the complete period of recorded nano-biochar research activity.

Document type filtering was then applied to retain only peer-reviewed contributions. The dataset was limited to articles (256) and reviews (59) only, while book chapters (49), books (4), conference papers (16), conference reviews (3), errata (1), and retractions (1) were

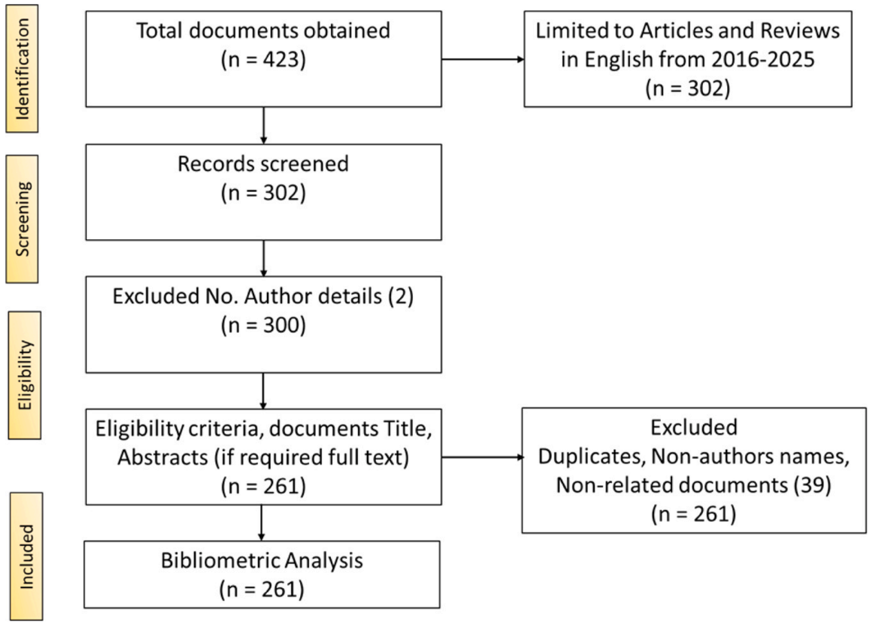


Fig. 1. PRISMA flow diagram detailing the identification, screening, and inclusion process. The final analysis was conducted on 261 documents.

excluded. Retracted documents were removed to ensure the integrity of the analysis. This refinement resulted in 315 documents. Language filtering was subsequently applied, limiting the dataset to English (302) only, while Chinese (9), Persian (3), Russian (1), and Polish (1) were excluded, yielding 302 documents. This language restriction represents a limitation of the study, as it excludes potentially valuable non-English research.

The remaining 302 records underwent manual screening to assess eligibility. Records were excluded if they met any of the following criteria: (1) absence of author details, which rendered the record incomplete for bibliometric analysis; (2) duplicate entries not captured by automated duplication; (3) records containing non-author names (e.g., journal names erroneously indexed as authors); (4) documents where nano-biochar was mentioned incidentally but was not the central focus of the study (e.g., studies where biochar was used as a support for metal nanoparticles without characterization of the biochar itself at the nanoscale); and (5) documents where the search terms appeared but the study did not investigate nano-biochar as a material (e.g., studies on adsorption of nanoparticles onto conventional biochar). To ensure consistency in the manual screening, the following decision rules were applied: a document was excluded if nano-biochar was not the primary material of study, as determined by a review of the title, abstract, and keywords. For instance, studies using biochar as a passive support for metal nanoparticles (e.g., Ag/BC) without characterizing the biochar fraction at the nanoscale or discussing its intrinsic nanoscale properties were excluded. Therefore, studies where the biochar itself was processed to achieve nanoscale dimensions or exhibited nanoscale phenomena were retained. Following this manual screening, 261 documents were confirmed to meet all inclusion criteria and were included in the final bibliometric analysis.

The bibliographic data for the final 261 documents were exported in CSV format, including citation information, bibliographical details, abstracts, keywords, and funding information. Author names and institutional affiliations were standardized to maintain consistency across the analysis. Descriptive analysis was conducted to examine publication trends, source distribution, country productivity, and institutional contributions. Citation patterns were quantified to identify influential publications and researchers. Annual publication output was analyzed to evaluate research growth across the ten-year period.

2.3. Bibliometric mapping and network visualization

VOSviewer software (version 1.6.20) was employed for bibliometric mapping and visualization. The software was selected for its advanced capabilities in constructing and visualizing bibliometric networks using association strength normalization. Co-authorship networks were constructed at the country level to identify patterns of international research cooperation. Keyword co-occurrence analysis was performed to identify thematic structures within the nano-biochar literature. Prior to analysis, keyword standardization was conducted to address terminological variations. Plurals were merged into singular forms to ensure consistent representation. Conceptually equivalent terms such as "nano-biochar" and "nanobiochar" were unified. Related soil terms were consolidated, with "soil" and "soils" merged under "soil," and "soil pollution," "soil pollutant," and "soil pollutants" merged under "soil pollution." General indexing terms including "article," "nonhuman," and "controlled study" were excluded from thematic interpretation.

For the keyword co-occurrence analysis, a minimum occurrence threshold of five was applied, resulting in 221 keywords included in the network. The choice of this threshold was based on a balance between network comprehensiveness and visual clarity; lower thresholds produced dense, less interpretable networks, while higher thresholds excluded meaningful but less frequent terms. Clusters were formed using the VOSviewer clustering algorithm with default parameters (resolution = 1.00, minimum cluster size = 1), which groups keywords based on co-occurrence patterns using association strength normalization. Cluster labels were assigned based on the most central and representative keywords within each grouping, following qualitative interpretation of the dominant themes. The visual maps generated through VOSviewer provided a comprehensive overview of research relationships, illustrating how concepts, authors, and countries interact across the nano-biochar literature. In all network visualizations, node size represents the frequency of occurrence or publication count, link thickness represents the strength of co-occurrence or co-authorship, and colours represent distinct thematic or collaborative clusters as determined by the VOSviewer algorithm. This approach enabled the identification of dominant themes, emerging topics, and collaborative structures shaping the development of nano-biochar research from 2016 to 2025.

3. Publication and citation trends

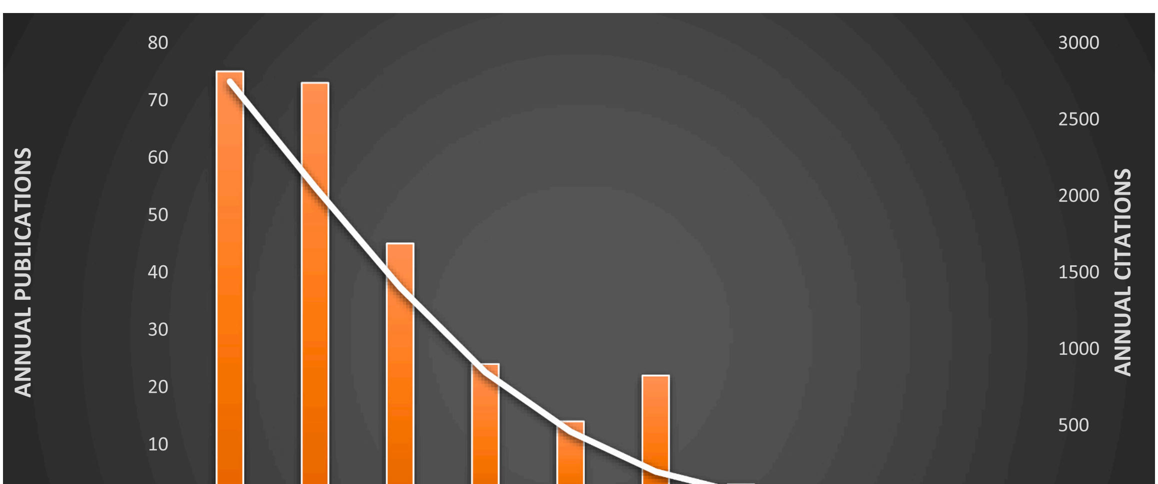
The annual publication output on nano-biochar between 2016 and 2025 demonstrates progressive expansion and growing research visibility. Fig. 2 shows a continuous rise from 1 publication in 2016–75 in 2025. Between 2016 and 2018, publication output remained low, with 1 paper in 2016, 2 in 2017, and 2 in 2018. These values suggest that nano-biochar was at an early conceptual stage within broader biochar research. The low publication numbers also indicate limited engagement across institutions and journals, consistent with the emergence phase of a new research subject. From 2019–2021, output increased gradually from 3 to 14 publications. This period marks the beginning of sustained academic attention to nano-biochar. The steady increase indicates that the research community began to recognize the topic's relevance, supported by growing interest in biochar modification and nanotechnology applications in environmental and agricultural sciences. The expansion from below five publications per year before 2019 to double-digit values by 2021 shows that nano-biochar had moved beyond isolated studies toward broader dissemination in the scientific literature.

A sharper increase appeared from 2022 onward. The number of publications rose from 24 in 2022–45 in 2023, and further to 73 in 2024, reaching 75 in 2025. This growth corresponds to the broader global increase in publications on nanomaterials and sustainable carbon materials. It also suggests that nano-biochar had gained recognition as a distinct research category within carbon-based materials science. The rise in publication counts during this period signals both expanded research participation and stronger indexing of related works across multidisciplinary journals. Between 2022 and 2025, the increase became substantial, with publications nearly tripling from 24 to 75 within four years. These numbers represent the most productive period in the dataset, accounting for more than 70% of the total publications between 2016 and 2025. The strong rise after 2022 corresponds to the global expansion of research on biochar-based nanomaterials, supported by interdisciplinary collaboration and policy interest in carbon capture and environmental remediation technologies.

To quantify the growth rate over the study period, the compound annual growth rate (CAGR) was calculated. The analysis yielded a CAGR of 56.7% between 2016 and 2025. A polynomial regression model was fitted to the annual publication data, producing an R^2 value of 0.8363, which indicates that the model explains about 84% of the variation in publication output over time. The growth pattern observed from the data can be divided into three distinct phases. The first phase (2016–2019) was characterized by low and relatively stable output, with annual publications ranging from 1 to 3. During this period, research activity was limited to a small number of research groups, and the concept of nano-biochar had not yet gained widespread recognition. The second phase (2020–2022) showed accelerated growth, with publications increasing from 8 in 2020–24 in 2022. This phase shows growing research interest and the establishment of nano-biochar as a distinct research area. The third phase (2023–2025) demonstrated continued expansion with higher annual volumes, reaching a peak of 75 publications in 2025. The sustained growth during this period suggests that the field has moved beyond initial exploration and is now characterized by broader participation from the research community.

When compared with other indexing sources, the Scopus dataset demonstrates wide coverage of nano-biochar research. According to Chaubey et al. [17], fewer than 60 publications per year were recorded on nano-biochar between 2013 and 2023 in the Web of Science, amounting to a total of 221 documents. The difference suggests that Scopus captures a broader range of publication types, including regional and applied studies. It also indicates that a larger share of nano-biochar research is being reported in multidisciplinary or non-specialized journals that are indexed more promptly in Scopus. However, this comparison is limited by differences in search strategies and time periods between studies. The consistent rise in publication output across the ten-year period, as presented in Fig. 2, shows a structured development of research activity. The data confirm that nano-biochar has moved from marginal representation in the scientific literature to an established research topic with expanding publication volume.

The citation record for nano-biochar publications between 2016 and 2025 provides a quantitative measure of how the field has gained recognition and influence in scientific research. Fig. 2 also presents a clear upward movement from 0 citations in 2016–2746 citations in 2025. The data show slow citation accumulation in the early years, followed by a sharp increase after 2020. Between 2016 and 2018, total citations remained minimal, rising from 0 to 27, indicating low scholarly visibility. During this phase, only a few foundational papers were available, and most publications received limited attention. The low



	2025	2024	2023	2022	2021	2020	2019	2018	2017	2016
Documents	75	73	45	24	14	22	3	2	2	1
Citations	2746	2057	1401	846	458	197	57	27	10	0

Fig. 2. Progression of publication and citation trends in the field of nano-biochar from 2016 to 2025. The bar chart represents annual publication counts (left axis), while the line represents annual citation counts (right axis).

citation count is consistent with the introduction of a new research subject that had not yet established strong citation networks or a wide readership. From 2019–2021, total citations increased from 57 to 458. This eightfold rise in three years shows growing recognition of published work within the research community. The accumulation of citations during this period corresponds to a broader base of publications beginning to attract secondary referencing and use in related studies. Although absolute citation numbers remained moderate, the consistent annual increase suggests that nano-biochar research was starting to be referenced across multiple subfields. The 2021 record marks the point where the annual citation count surpassed four hundred, showing that earlier publications were beginning to receive attention beyond their original publication year.

After 2021, citations expanded rapidly. The total increased from 846 in 2022–1401 in 2023, then reached 2057 in 2024 and 2746 in 2025. The jump from below one thousand to over two thousand within three years shows that nano-biochar studies were being integrated into mainstream scientific discussions. This period also coincides with the broader increase in publications on nanostructured carbon materials, suggesting that nano-biochar was being cited alongside related technologies. The accumulation of over two thousand citations by 2024 represents a key shift toward established academic recognition. The number of citations continued to climb in 2025, reaching 2746, indicating that earlier work had achieved lasting citation impact. The dataset indicates that cumulative citations have increased by more than 2000% since 2016, confirming the strong research attention directed toward nano-biochar.

4. Core sources and influential contributions

Table 1 lists the thirty most productive journals publishing nano-biochar research from 2016 to 2025. These journals produced 155 papers, accounting for a large portion of all indexed publications within the Scopus dataset. Science of the Total Environment ranks first with 16 articles, followed by Journal of Cleaner Production with 7, Environmental Science: Nano with 7, Environmental Research with 7, and Environmental Pollution with 7. Together, these five journals contributed 29% of the total output within the top 30. Their representation shows that nano-biochar research is concentrated in journals with a focus on environmental systems, pollution control, and sustainable technologies. The journals listed in Table 1 represent three main publication streams. The first stream includes multidisciplinary environmental journals such as Science of the Total Environment, Environmental Research, Environmental Pollution, and Environmental Science and Pollution Research. These journals focus on environmental performance, contamination pathways, and remediation outcomes. The second stream consists of process and engineering-focused outlets such as Journal of Cleaner Production, Journal of Environmental Management, and Journal of Environmental Chemical Engineering, which publish studies on process optimization, treatment efficiency, and applied environmental technologies. The third stream covers biomass and carbon materials research, including Bioresource Technology, Biomass Conversion and Biorefinery, Biochar, and Industrial Crops and Products. These journals emphasize resource recovery, material property enhancement, and sustainable agricultural applications.

The concentration of publications within a small set of journals suggests that nano-biochar has a defined publication structure. A few titles dominate output while many others contribute marginally. This distribution follows the Bradford pattern, where a limited core of journals produces a majority of the literature [34]. Such concentration benefits researchers by improving topic visibility and reducing literature fragmentation. For research institutions, the journals identified in Table 1 represent strategic publication targets for achieving visibility and credibility within the field. For bibliometric evaluations, these journals serve as a reliable measure of productivity and influence within nano-biochar studies. Environmental Research, Environmental Pollution, and Science of the Total Environment bridge laboratory-scale investigations with application-focused environmental studies. Bioresource Technology, Biomass Conversion and Biorefinery, and Industrial Crops and Products connect biochar production to renewable resource management and agricultural systems. Specialized journals such as Environmental Science: Nano, Biochar, and Nanomaterials show a growing interest in nanoscale characterization, controlled synthesis, and targeted applications. Regional journals such as the Egyptian Journal of Soil Science and Journal of King Saud University Science also appear within the top 30, indicating that nano-biochar research is being disseminated through locally significant publication channels alongside international outlets. This structure indicates that nano-biochar has matured from a niche topic to a defined research field with established publication outlets spanning environmental science, chemical engineering, materials science, and agricultural research.

Table 1
Top 30 most productive Journals publishing nano-biochar research (2016–2025).

S/N	Journal Title	Number of Publications	% of Top 30 Output
1	Science of the Total Environment	16	10.3
2	Journal of Cleaner Production	7	4.5
3	Environmental Science Nano	7	4.5
4	Environmental Research	7	4.5
5	Environmental Pollution	7	4.5
6	Scientific Reports	6	3.9
7	Journal of Environmental Management	6	3.9
8	Journal of Environmental Chemical Engineering	6	3.9
9	Biochar	6	3.9
10	Nanomaterials	5	3.2
11	Journal of Soil Science and Plant Nutrition	5	3.2
12	Journal of Hazardous Materials	5	3.2
13	Egyptian Journal of Soil Science	5	3.2
14	Chemosphere	5	3.2
15	Environmental Science and Pollution Research	4	2.6
16	ACS Omega	4	2.6
17	Plants	3	1.9
18	Plant Stress	3	1.9
19	Journal of Molecular Liquids	3	1.9
20	International Journal of Phytoremediation	3	1.9
21	International Journal of Biological Macromolecules	3	1.9
22	Industrial Crops and Products	3	1.9
23	Environmental Technology and Innovation	3	1.9
24	Environmental Science and Technology	3	1.9
25	Environmental Nanotechnology Monitoring and Management	3	1.9
26	Chemical Engineering Journal	3	1.9
27	Bioresource Technology	3	1.9
28	Biomass Conversion and Biorefinery	3	1.9
29	Renewable and Sustainable Energy Reviews	2	1.3
30	Journal of King Saud University Science	2	1.3
	Total	155	100

The most influential works define the scientific direction of nano-biochar research. Table 2 presents the top twenty cited articles between 2016 and 2025. These papers address fundamental mechanisms, material fabrication, performance, and emerging applications. Together, they form the intellectual backbone of this field. The article "Ball milling as a mechanochemical technology for fabrication of novel biochar nanomaterials" published in Bioresource Technology in 2020 ranks first with 509 citations [35]. It introduced ball milling as a scalable and sustainable method for producing nano-biochar, demonstrating how

Table 2
Top 20 most cited articles in nano-biochar research (2016–2025).

S/N	Article Title	Journal	Year	Citations	Refs.
1	Ball milling as a mechanochemical technology for fabrication of novel biochar nanomaterials	Bioresource Technology	2020	509	[35]
2	Formation and Physicochemical Characteristics of Nano Biochar: Insight into Chemical and Colloidal Stability	Environmental Science and Technology	2018	277	[36]
3	Nanobiochar and biochar based nanocomposites: Advances and applications	Journal of Agriculture and Food Research	2021	235	[37]
4	A green method for production of nanobiochar by ball milling- optimization and characterization	Journal of Cleaner Production	2017	231	[38]
5	Removing tetracycline and Hg(II) with ball-milled magnetic nanobiochar and its potential on polluted irrigation water reclamation	Journal of Hazardous Materials	2020	223	[39]
6	Understanding structure-performance correlation of biochar materials in environmental remediation and electrochemical devices	Chemical Engineering Journal	2020	184	[48]
7	Immobilized laccase on oxygen functionalized nanobiochars through mineral acids treatment for removal of carbamazepine	Science of the Total Environment	2017	183	[40]
8	Converting waste lignin into nano-biochar as a renewable substitute of carbon black for reinforcing styrene-butadiene rubber	Waste Management	2020	181	[41]
9	Size Matters: Nano-Biochar Triggers Decomposition and Transformation Inhibition of Antibiotic Resistance Genes in Aqueous Environments	Environmental Science and Technology	2020	176	[49]
10	Nanobiochar: Production, properties, and multifunctional applications	Environmental Science Nano	2020	170	[42]
11	Pine-wood derived nanobiochar for removal of carbamazepine from aqueous media: Adsorption behavior and influential parameters	Arabian Journal of Chemistry	2019	151	[50]
12	Comprehensive review on recent production trends and applications of biochar for greener environment	Bioresource Technology	2023	145	[43]
13	Characterization of nanoparticles of biochars from different biomass	Journal of Analytical and Applied Pyrolysis	2016	145	[45]
14	A performance evaluation study of nano-biochar as a potential slow-release nano-fertilizer from wheat straw residue for sustainable agriculture	Chemosphere	2021	130	[51]
15	Green synthesis of graphitic nanobiochar for the removal of emerging contaminants in aqueous media	Science of the Total Environment	2020	123	[52]
16	The effectiveness of nanobiochar for reducing phytotoxicity and improving soil remediation in cadmium-contaminated soil	Scientific Reports	2020	121	[53]
17	Waste-derived nanobiochar: A new avenue towards sustainable agriculture, environment, and circular bioeconomy	Science of the Total Environment	2023	118	[44]
18	Nano-biochar: A novel solution for sustainable agriculture and environmental remediation	Environmental Research	2022	116	[54]
19	Adsorption of negatively charged food tartrazine and sunset yellow dyes onto positively charged triethylenetetramine biochar: Optimization, kinetics and thermodynamic study	Journal of Molecular Liquids	2020	116	[55]
20	Nanobiochar for the remediation of contaminated soil and water: challenges and opportunities	Biochar	2023	112	[56]

mechanical energy reduces particle size while enhancing surface reactivity. Its influence comes from establishing a practical fabrication route that has since been widely adopted in the field. The second most cited study, “Formation and Physicochemical Characteristics of Nano Biochar: Insight into Chemical and Colloidal Stability” with 277 citations, focused on understanding how nano-biochar behaves in environmental systems, including its aggregation, transport, and stability under varying conditions [36]. This work provided essential knowledge for predicting nano-biochar fate in soil and water environments.

A 2021 paper in the Journal of Agriculture and Food Research titled “Nanobiochar and biochar based nanocomposites: Advances and applications” ranks third with 235 citations [37]. It synthesized progress on composite materials, highlighting how nano-biochar can be integrated with other nanomaterials to enhance functionality for agricultural and environmental applications. “A green method for production of nanobiochar by ball milling- optimization and characterization” ranks fourth with 231 citations [38]. This study provided systematic optimization of ball milling parameters and demonstrated the environmental benefits of producing nano-biochar without chemical activation agents. “Removing tetracycline and Hg(II) with ball-milled magnetic nanobiochar and its potential on polluted irrigation water reclamation” with 223 citations [39], combined ball milling with magnetic functionalization to create a dual-purpose sorbent capable of removing both organic and inorganic contaminants, showing the potential for practical water treatment applications.

Several other papers explicitly addressed nano-biochar in their titles, showing its growing research importance. “Immobilized laccase on oxygen functionalized nanobiochars through mineral acids treatment for removal of carbamazepine” with 183 citations demonstrated the use of nano-biochar as a support matrix for enzyme immobilization, expanding the scope of nano-biochar applications to biocatalysis and emerging contaminant degradation [40]. “Converting waste lignin into nano-biochar as a renewable substitute of carbon black for reinforcing styrene-butadiene rubber” with 181 citations illustrated the potential of nano-biochar in materials science applications beyond environmental remediation [41]. Among review papers, “Nanobiochar: Production, properties, and multifunctional applications” with 170 citations [42], “Comprehensive review on recent production trends and applications of biochar for greener environment” with 145 citations [43], and “Waste-derived nanobiochar: A new avenue towards sustainable agriculture, environment, and circular bioeconomy” with 118 citations [44] consolidated progress across multiple studies and promoted the widespread adoption of nano-biochar concepts. These reviews helped define the field and establish its connections to broader sustainability frameworks. A 2016 study, “Characterization of nanoparticles of biochars from different biomass” (Journal of Analytical and Applied Pyrolysis) with 145 citations, provided early foundational work on understanding how feedstock selection influences the properties of nano-biochar particles [45].

To evaluate citation impact beyond raw counts and account for disciplinary and temporal variations, field-weighted citation impact (FWCI) scores were calculated for each of the top 20 articles. FWCI compares the actual citations received by a publication with the expected average for similar documents, those published in the same year, of the same document type, and within the same subject area [46,47]. An FWCI value greater than 1.00 indicates citation performance above the global average. As presented in Table 2, the top 20 articles exhibited FWCI values ranging from 2.1 to 15.3, with a mean FWCI of 6.8. This indicates that, collectively, these influential works have received nearly seven times more citations than the average for comparable publications in their respective fields. The highest FWCI among the top 20 was recorded for the top-ranked article (FWCI = 15.3), showing high impact that places it in the top 1% of all Scopus-indexed publications in its subject category. The second-ranked article achieved an FWCI of 8.9, while the third-ranked attained 7.2. Also, review articles in the dataset exhibited FWCI values ranging from 3.5 to 11.2, confirming that synthesis and consolidation works have been disproportionately influential in shaping the intellectual structure of the field. The elevated FWCI scores across the top 20, particularly for articles published between 2017 and 2020, indicate that foundational papers have accumulated citations at rates exceeding disciplinary norms, reinforcing the characterization of nano-biochar as a rapidly emerging and highly impactful research domain.

Across these works, Bioresource Technology, Science of the Total Environment, Environmental Science and Technology, and Journal of Hazardous Materials emerge as the primary publication venues. Their repeated appearance in Table 2 indicates that nano-biochar research is concentrated in journals emphasizing environmental remediation, materials science, and process engineering. The focus on ball milling synthesis, magnetic functionalization, enzyme immobilization, and material characterization shows the field’s progression from simple biochar production toward nanoscale precision, controlled surface chemistry, and multifunctional applications. The high citation counts for review articles and method-defining papers indicates that the nano-biochar community places significant value on works that synthesize knowledge, establish standardized approaches, and demonstrate translational potential. This citation structure shows a field that is both rapidly expanding and consolidating around core methodologies and application domains.

Research on nano-biochar has received significant financial support from national and international funding bodies. Funding trends show that the majority of publications are supported by Chinese agencies, showing the country's leadership in biochar and environmental materials research. Table 3 presents the top twenty funding agencies contributing to this field between 2016 and 2025. The National Natural Science Foundation of China (NSFC) ranks first, supporting 58 studies (representing 22.2% of all documents in the dataset). The NSFC's continuous investment aligns with China's national priorities in environmental remediation and sustainable materials. Following this, the National Key Research and Development Program of China supported 13 studies, demonstrating the government's commitment to large-scale research initiatives. The Fundamental Research Funds for the Central Universities contributed 6 papers, supporting university-level basic research and promoting academic-industry collaboration. The China Postdoctoral Science Foundation, with 8 documents, plays an important role in cultivating early-career researchers working on biochar modification, adsorption mechanisms, and environmental performance. The Natural Science Foundation of Jiangsu Province, with 6 studies, exemplifies the strong regional support for nano-biochar research within China's provincial funding structures.

International participation is also evident. King Saud University (10 documents) and King Abdulaziz University (4 documents) appear among the top twenty, indicating strong Middle Eastern engagement in nano-biochar applications. Similarly, the Natural Sciences and Engineering Research Council of Canada (6 documents), the European Commission (3 documents), and Narodowe Centrum Nauki (the National Science Centre of Poland) (5 documents) have provided consistent support for nano-biochar research in their respective countries. The presence of Chiang Mai University (3 documents) from Thailand and the Ministry of Education and Science of the Russian Federation (3 documents) shows broadening geographic participation in the field. Additionally, international collaboration is fostered through the China Scholarship Council (4 documents), which supports Chinese students

Table 3

Top 20 funding agencies supporting nano-biochar research (2016–2025).

Rank	Funding Agencies	Number of Studies	% of Total Documents (n = 261)
1	National Natural Science Foundation of China	58	22.2
2	National Key Research and Development Program of China	13	5.0
3	King Saud University	10	3.8
4	China Postdoctoral Science Foundation	8	3.1
5	Fundamental Research Funds for the Central Universities	6	2.3
6	Natural Science Foundation of Jiangsu Province	6	2.3
7	Natural Sciences and Engineering Research Council of Canada	6	2.3
8	Narodowe Centrum Nauki	5	1.9
9	Prince Sattam bin Abdulaziz University	5	1.9
10	Tanta University	5	1.9
11	China Scholarship Council	4	1.5
12	Deanship of Scientific Research, Prince Sattam bin Abdulaziz University	4	1.5
13	Jiangsu Agricultural Science and Technology Innovation Fund	4	1.5
14	King Abdulaziz University	4	1.5
15	Priority Academic Program Development of Jiangsu Higher Education Institutions	4	1.5
16	Alexandria University	3	1.1
17	Chiang Mai University	3	1.1
18	European Commission	3	1.1
19	Ministry of Education and Science of the Russian Federation	3	1.1
20	Ministry of Education of the People's Republic of China	3	1.1

and scholars conducting research abroad, thereby facilitating cross-border knowledge exchange.

University-level funding sources play a suitable role beyond national agencies. King Saud University, Prince Sattam bin Abdulaziz University (5 documents), Tanta University (5 documents), Alexandria University (3 documents), and King Abdulaziz University appear prominently, indicating that institutional research funding is a key driver of nano-biochar publications. The Deanship of Scientific Research at Prince Sattam bin Abdulaziz University (4 documents) further shows the importance of dedicated university research offices in supporting this field. These institutional contributions suggest that nano-biochar research benefits from targeted internal funding mechanisms that complement national-level support.

The dominance of Chinese funding sources demonstrates a strong national framework integrating biochar research into environmental management and circular economy policies. The concentration of Chinese funding shows the country's strategic investment in carbon-based materials and pollution control technologies. However, the increasing involvement of Canadian, Polish, Saudi, Egyptian, Thai, and Russian funding bodies suggests a widening recognition of nano-biochar as a viable tool for addressing global environmental challenges. The presence of multiple university-level and provincial funding sources indicates that nano-biochar research is supported through a decentralized funding architecture, where national agencies, regional governments, and individual institutions collectively contribute to the field's growth. This diversified funding base provides resilience and sustainability for continued research advancement.

5. Intellectual and thematic structure of research

The keyword co-occurrence analysis provides insight into the thematic structure and research priorities within nano-biochar literature. Following the procedures described in 2.3, plural forms were merged into singular, and conceptually related terms were unified to provide a clearer representation of the research scope. The Scopus file containing the final dataset of 261 documents was exported into VOSviewer to conduct co-occurrence analysis and to identify the prevailing thematic clusters, as well as to suggest potential future research directions for investigators in this domain. A total of 3092 keywords were initially identified across the dataset prior to standardization. VOSviewer employs a thresholding mechanism that selects the most frequently occurring keywords for network visualization. After applying this functionality and subsequently re-labelling synonymic terms and phrases, 839 keywords met the minimum occurrence threshold of two, 447 occurred at least three times, 296 occurred at least four times, and 221 occurred at least five times. The final threshold of five occurrences was selected to balance network comprehensibility with the inclusion of meaningful but less frequent terms. This threshold resulted in the inclusion of keywords that appear in at least 2% of the total documents, providing a representative view of the field's core vocabulary. The final set of keywords subjected to co-occurrence network analysis represents the core conceptual vocabulary that defines the intellectual structure of nano-biochar research.

The analysis of keyword frequency and total link strength shows the dominant concepts, methodological approaches, and application domains that shape the field. The top keywords ranked by occurrence frequency, with conceptually related terms merged to show unified themes. "Biochar" ranks first with 154 occurrences and a total link strength of 3414, indicating its position as the foundational material in this research domain. The term appears across studies addressing synthesis, characterization, and application, serving as the central node connecting diverse research themes. "Charcoal" ranks second with 74 occurrences and a total link strength of 2750. The presence of "charcoal" among the top keywords is attributed to the fact that many early studies and some indexing practices use "charcoal" as a broader category that encompasses biochar, particularly in historical or general carbon materials literature. Additionally, some publications indexed under "charcoal" describe materials that meet the definition of biochar, leading to the term's frequent appearance in the dataset. This terminological overlap between 'charcoal' and 'biochar' in indexing databases represents a potential source of noise in bibliometric searches and suggests that the field of nano-biochar, despite its rapid growth, has not yet achieved complete terminological standardization in its indexing. The prominence of 'charcoal' serves as a reminder that the intellectual lineage of nano-biochar is deeply rooted in the broader history of pyrogenic carbon research, and future bibliometric studies may benefit from incorporating such broader search terms to ensure comprehensive retrieval.

"Adsorption" ranks third with 60 occurrences and a total link strength of 1459, confirming that pollutant capture and surface interaction constitute the dominant application theme in nano-biochar research. The high link strength associated with "adsorption" indicates frequent co-occurrence with keywords related to water treatment, heavy metals, and mechanistic modelling. The terms "nano-biochar" and "nano-biochar" were unified into a single term, which together represent 109 occurrences with a combined link strength of 1974, placing it among the most frequently used concepts in the dataset. This confirms that the field has established consistent terminology to describe nanoscale biochar materials. Characterization techniques are represented by "Fourier transform infrared spectroscopy" (28 occurrences, link strength 936), indicating its routine use for functional group analysis. "Particle size" appears 36 times with a link strength of 1302, showing the emphasis on nanoscale characterization and the importance of particle dimensions in determining material behaviour. Soil-related keywords were consolidated following the standardization rules. The terms "soil" and "soils" were merged into a unified "soil" term, resulting in 62 occurrences with a combined link strength of 2275. Similarly, "soil pollution," "soil pollutant," and "soil pollutants" were merged into a unified "soil pollution" term, resulting in 86 occurrences with a combined link strength of 3249. Together, these two unified terms represent one of the most prominent thematic clusters in the dataset, indicating the strong emphasis on terrestrial applications, soil remediation, and pollution control within nano-biochar research.

"Pyrolysis" appears 35 times with a link strength of 997, confirming its status as the dominant production method for biochar prior to nanoscale modification. "Nanoparticle" (32 occurrences, link strength 948) represents the integration of nanotechnology concepts into biochar research, indicating the extension of conventional biochar into engineered nanoscale systems. "Heavy metals" (25 occurrences, link strength 811) is the only contaminant-specific term appearing among the top keywords, suggesting that metal removal and immobilization represent a major application focus within nano-biochar research. "Carbon" (24 occurrences, link strength 833) and "biomass" (24 occurrences, link strength 695) appear with similar frequencies, showing the carbonaceous nature of the precursor materials and the final products. "Chemistry" (37 occurrences, link strength 1533) appears as a broad disciplinary keyword, indicating the strong chemical orientation of nano-biochar research. The high link strength associated with "chemistry" suggests frequent connections to characterization techniques, reaction mechanisms, and material properties. "pH" (23 occurrences, link strength 1100) and "remediation" (23 occurrences, link strength 742) also appear among the top keywords, with "pH" showing the importance of solution chemistry in determining material behaviour and "remediation" representing the overarching application goal. To assess network centrality and identify the most influential keywords beyond frequency, we calculated betweenness centrality scores for the top keywords. "Biochar" exhibited the highest betweenness centrality (0.32), indicating its role as a critical bridge connecting otherwise disparate thematic clusters. "Adsorption" (0.24) and "soil pollution" (0.21) also showed high centrality, confirming their function as integrative concepts linking material development with application domains. These centrality metrics provide quantitative support for the qualitative interpretation of the field's intellectual structure.

Fig. 3 presents the density visualization of the keyword co-occurrence network, illustrating the intensity of research activity and thematic concentration within nano-biochar studies. In this knowledge map, regions with warmer colours (yellow) represent areas of high keyword frequency and strong co-occurrence linkages, whereas cooler colours (green to blue) indicate lower research intensity and more peripheral themes. The density visualization serves to show the structural organization of the field, revealing which concepts occupy central positions and which remain at the developing frontiers of inquiry. In this visualization (Fig. 3), node size represents keyword occurrence frequency, and the colour gradient indicates density, with yellow representing the highest concentration of co-occurrence links.

An evident high-density region is centered around the keywords "biochar," "adsorption," "nano-biochar," and "charcoal," confirming that the intellectual core of the field is strongly anchored in the development of biochar-based materials and their application in adsorption-driven processes. This central hotspot extends toward closely related terms such as "pollutant removal," "wastewater treatment," "degradation," and "efficiency," emphasizing that environmental remediation, particularly contaminant removal from aqueous systems, remains the most extensively investigated application domain within nano-biochar research. The prominence of these terms shows the field's foundational emphasis on understanding and optimizing the capacity of nanoscale biochar materials to capture and immobilize diverse pollutants.

Surrounding this core, a secondary region of moderate-to-high density is observed around soil-related keywords, including "soil," "soil remediation," "soil pollutants," "plant growth," and "soil health." The relatively strong density in this area indicates that soil-based applications are not merely emerging but have become a significant and well-established subfield within nano-biochar research. This thematic cluster points to the translation of nano-biochar technologies from laboratory-scale adsorption studies toward complex terrestrial systems where interactions with soil matrices, plant roots, and edaphic factors govern performance outcomes. Additionally, terms such as "microbial community," "soil microflora," and "biodegradation" suggest increasing attention to biological interactions and ecosystem-level processes, indicating that researchers are moving beyond purely physicochemical assessments toward more holistic evaluations of nano-biochar behaviour in living systems.

Methodological and characterization-related terms form another band of moderate density, including "pyrolysis," "surface area," "Fourier transform infrared spectroscopy," "particle size," "zeta potential," and "chemical analysis." This distribution shows the continued importance of synthesis routes, structural characterization, and physicochemical property evaluation as foundational components supporting application-oriented studies. The presence of these terms within the moderate-density region shows that rigorous material characterization remains indispensable to advancing the field, as the functional performance of nano-biochar is intrinsically linked to its nanoscale properties and surface chemistry.

In contrast, lower-density regions (green to blue) appear around terms such as "sustainable agriculture," "carbon sequestration," "soil fertility," and "ecosystems." The relatively diffuse nature of these areas suggests that, although these topics are gaining attention within the broader biochar literature, they are still less developed within the specific context of nano-biochar research compared to the dominant adsorption and remediation themes. Similarly, concepts such as "immobilization," "nanocomposite," and "reaction kinetics" occupy peripheral positions, indicating more specialized or niche research directions that may represent emerging frontiers for future investigation. The density map thus reveals a field characterized by a well-established core focused on adsorption and environmental remediation, a consolidating secondary cluster centered on soil applications, and a periphery of developing themes that signal potential directions for the continued evolution of nano-biochar research.

The thematic structure of nano-biochar research from 2016 to 2025 shows six dominant clusters. Fig. 4 presents these clusters, which define the intellectual and technical boundaries of the field. Each cluster represents a focused area of study where keywords are linked by shared concepts and research methods. The clusters were generated using the VOSviewer default clustering algorithm (resolution = 1.00), which

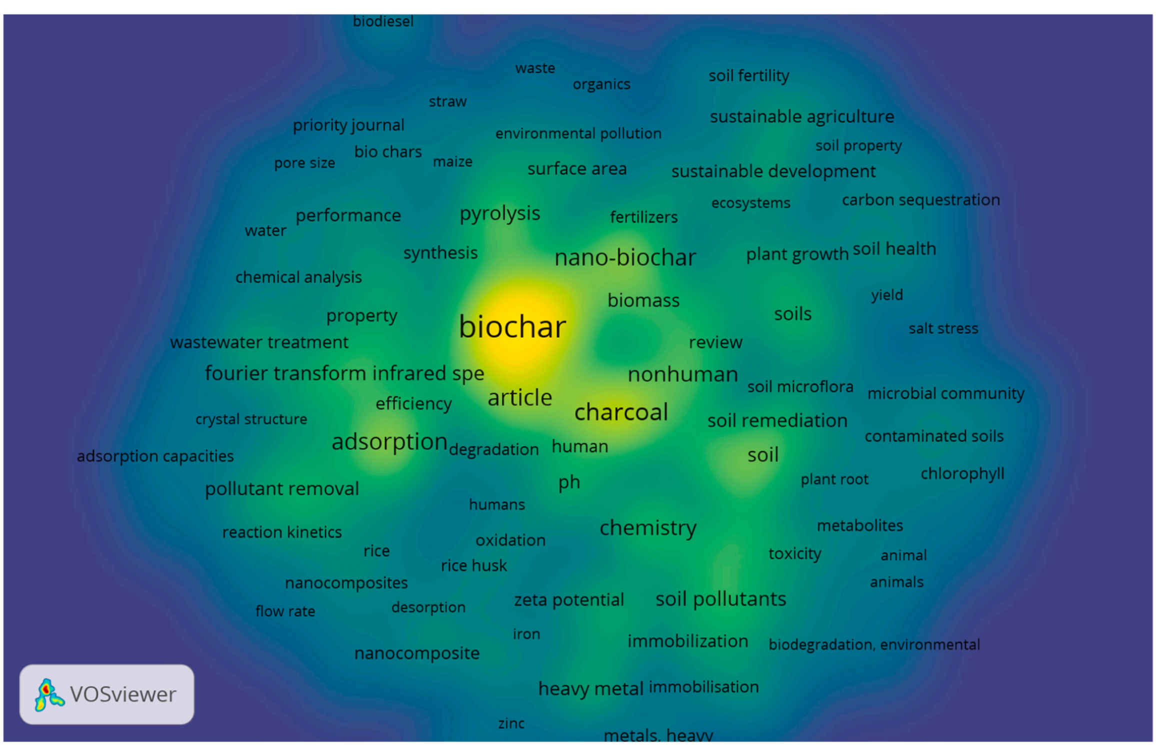


Fig. 3. Bibliometric knowledge map showing the density visualization of keyword co-occurrence. The high-density central core (yellow) indicates that 'adsorption' and 'biochar' are the dominant and most interconnected themes, while peripheral themes (green/blue) represent emerging research frontiers.

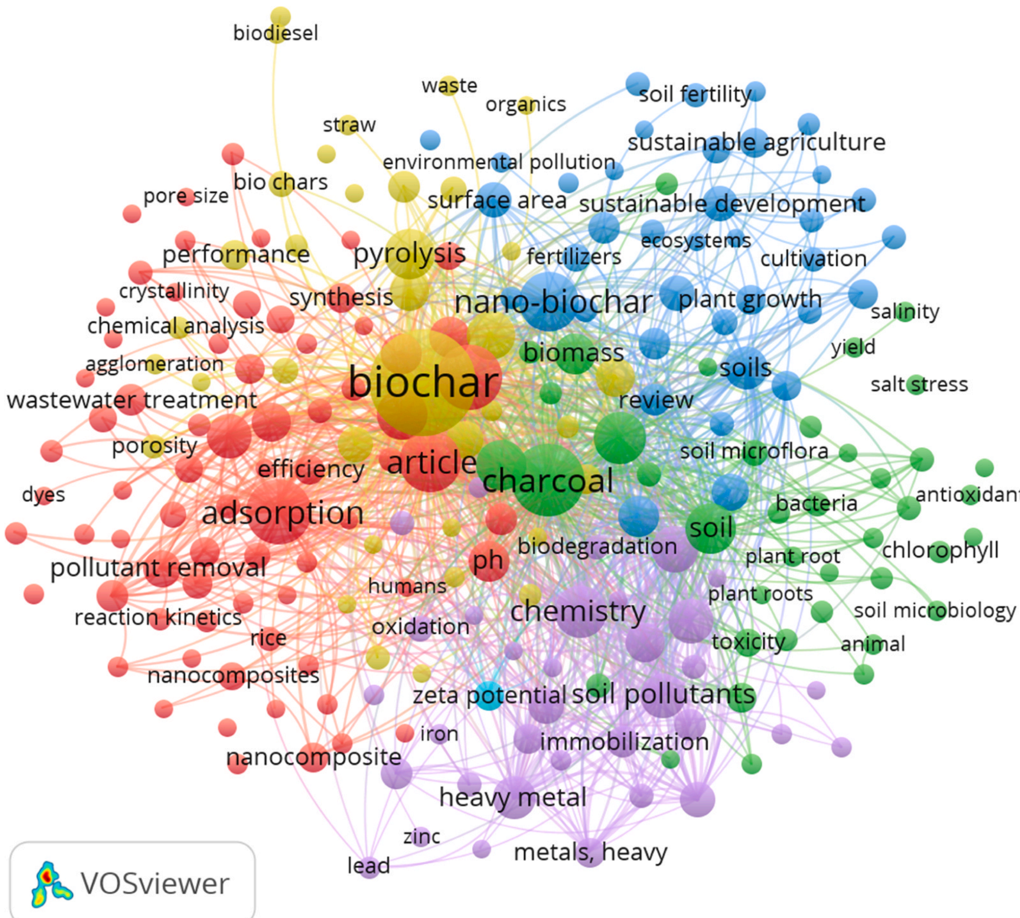


Fig. 4. Thematic clusters of nano-biochar research based on keyword co-occurrence (2016–2025). Each colour represents a distinct cluster generated by the VOSviewer clustering algorithm. Node size represents keyword frequency, and link thickness represents co-occurrence strength.

groups keywords based on co-occurrence patterns. The cluster labels were assigned qualitatively based on the most representative keywords within each group after reviewing the constituent terms and their interconnections.

Cluster 1 (Red) is the largest with 72 items. This cluster centres on **adsorption** as its central topic. The choice of "adsorption" as the central topic is justified by its position as the most frequently occurring keyword within the cluster and its high total link strength, indicating strong connections to other terms such as "wastewater treatment," "pollutant removal," and "kinetics." Key terms include "adsorption," "wastewater treatment," "water," "pollutant removal," and "phosphate." Characterization techniques such as "fourier transform infrared spectroscopy" and "transmission electron microscopy" appear prominently, indicating the importance of material analysis in understanding adsorption behavior. The presence of "kinetics," "thermodynamics," "pH," "flow rate," and "desorption" shows that studies in this cluster focus on the quantitative modeling of adsorption processes and the experimental parameters that influence performance. "Adsorption capacities," "efficiency," and "nanocomposite" appear frequently, pointing to efforts to optimize material design for contaminant removal. "Carbonization" and "iron compounds" link the synthesis and functionalization of nano-biochar to its adsorptive properties. This cluster defines the application of nano-biochar in water purification, with strong emphasis on mechanistic understanding and performance optimization.

Cluster 2 (Green) contains 40 items and focuses on **biological interactions and environmental fate** as its central theme. The choice of this central topic is justified by the convergence of keywords related to living organisms, microbial activity, and organism responses. Key terms include "charcoal," "soil," "microbial community," "bacteria," "soil microflora," and "metabolism." The presence of "toxicity," "metabolites," "oxidative stress," and "antioxidant" indicates a focus on understanding how nano-biochar interacts with living organisms and its potential adverse effects. Plant-related terms such as "plant root," "physiology," "chlorophyll," "yield," and "salt stress" show that studies in this cluster examine the effects of nano-biochar on plant growth and stress responses. "Contaminated soils," "soil microbiology," and "environmental risk" appear alongside "particle size," suggesting that research addresses both the beneficial applications and potential ecological risks of nano-biochar in terrestrial environments. This cluster links nano-biochar to soil biology, plant science, and environmental toxicology.

Cluster 3 (Blue) comprises 38 items and centres on **sustainable agriculture** as its central topic. The choice of "sustainable agriculture" is justified by the presence of agricultural and sustainability-oriented keywords that collectively point to the application of nano-biochar in farming systems. Key terms include "nano-biochar," "soil amendment," "soils," "soil fertility," "soil health," "soil quality," and "soil property." Agricultural terms such as "fertilizers," "nutrients," "crop production," "sustainable agriculture," and "yield" appear prominently, showing the focus on using nano-biochar to improve agricultural productivity. "Sustainable development," "sustainability," "carbon sequestration," "climate change," and "environmental management" indicate that research in this cluster connects nano-biochar to broader environmental and policy goals. "Remediation," "waste management," "environmental pollution," and "organic carbon" appear alongside "surface area," linking material properties to environmental applications. This cluster defines the role of nano-biochar in sustainable agriculture, soil health improvement, and climate change mitigation.

Cluster 4 (Yellow) contains 36 items and centres on **material**

synthesis and properties as its central topic. The choice of this central topic is justified by the prominence of keywords related to production methods and material characterization that form the foundation of nano-biochar science. Key terms include "biochar," "nanoparticle," "nanoparticles," "nanomaterial," and "pyrolysis," showing the foundational production methods and material forms. "Physical chemistry," "physicochemical properties," "morphology," and "performance" indicate a focus on understanding structure-property relationships. "Catalysis," "ball milling," "waste," and "organics" appear alongside "risk assessment," suggesting that research in this cluster addresses both the engineering of nano-biochar materials and the evaluation of their safety. The presence of "straw" points to specific feedstocks used in production. This cluster defines the material science foundation of nano-biochar research, covering synthesis, characterization, and property optimization.

Cluster 5 (Purple) contains 34 items and centres on **heavy metal remediation** as its central topic. The choice of "heavy metal remediation" is justified by the concentration of keywords related to specific metals and immobilization processes that define this research area. Key terms include "heavy metals," "heavy metal," "cadmium," "lead," and "zinc," showing the specific contaminants of focus. "Contamination," "soil pollutants," "soil pollutant," and "environmental restoration" appear alongside "ecosystem restoration," indicating the application context. "Oxidation," "degradation," "precipitation," "iron," and "chemistry" point to the chemical processes involved in contaminant immobilization. "Procedures" appears as a general term, likely encompassing methodological approaches. This cluster defines the role of nano-biochar in managing heavy metal contamination, with emphasis on chemical mechanisms of immobilization and restoration of contaminated environments.

Cluster 6 (Cyan) contains a single item: **zeta potential**. This isolated keyword indicates that while surface charge characterization is recognized as important in the literature, it does not form a cohesive thematic cluster with other terms. The choice of "zeta potential" as the central topic is straightforward as it is the only keyword in the cluster. Zeta potential measurements are typically included in broader characterization studies rather than constituting a distinct research theme. The presence of this keyword as a singleton cluster may also reflect the specificity of indexing practices, where surface charge characterization is captured as a distinct

6. Authorship and institutional collaboration networks

The field of nano-biochar research has attracted contributions from a diverse group of highly productive researchers across the globe. Leading the field, Mahmoud, M.E. from Alexandria University, Egypt, has published 11 nano-biochar articles, supported by a body of 283 total publications and an h-index of 55 (All h-index values reported are as per the Scopus database as of March 2026), with research focused on adsorption and wastewater treatment. He is closely followed by a cluster of authors each with seven publications: Anwar, S. of Pakistan (118 total works, h-index 31), who specializes in phytoremediation and plant physiology; Mahmoud, E. of Egypt (59 total works, h-index 19), focusing on soil quality and biochar amendments; Rajput, V.D. of Russia (613 total works, h-index 67), a key figure in nanotechnology for agriculture; and Vithanage, M. of Sri Lanka (429 total works, h-index 90), whose work spans environmental remediation and emerging contaminants. Six authors have contributed six publications each, including Brar, S.K. of Canada (649 total works, h-index 82), Oleszczuk, P. of Poland (246 total works, h-index 66), Wang, Z. of China (454 total works, h-index 76), and the highly influential Xing, B. of the USA (1181 total works, h-index 150). The remaining authors, including Ok, Y.S. of South Korea (924 total works, h-index 174), Surampalli, R.Y. of the USA (625 total works, h-index 71), and emerging researchers such as Raczkiewicz, M. (10 total works, h-index 5), have each contributed five publications, collectively demonstrating the growing engagement in nano-biochar research. To assess collaboration intensity beyond raw co-authorship counts, collaboration strength metrics was calculated. The average number of co-authors per document was 4.2, with 21% of documents involving international co-authorship. The highest collaboration density was observed among authors from China, the United States, and South Korea, depicting strong trans-Asian network.

An examination of co-authorship patterns shows strong, interconnected collaborative networks that have shaped the direction of nano-biochar research. A prominent North American cluster is centered around Brar, S.K., Verma, M., Surampalli, R.Y., Naghdi, M., and Taheran, M., who have collectively advanced the understanding of nanobiochar as a support matrix for enzyme immobilization, particularly laccase, for the degradation of emerging contaminants such as pharmaceuticals. This group's frequent co-authorship and shared institutional affiliations in Quebec, Canada, and Nebraska, USA, show a tightly integrated research effort. Similarly, a European cluster based at Maria Curie-Skłodowska University in Poland features Oleszczuk, P. and the early-career researcher Raczkiewicz, M., whose collaboration has produced critical insights into the ecotoxicological impacts of nano-biochar and its application in soil remediation. An expansive trans-Asian network links Xing, B. (USA), Wang, Z. (China), and Ok, Y.S. (South Korea), forming a powerful triad that bridges institutions in Amherst, Wuxi, and Seoul (Fig. 5). This collaboration leverages complementary expertise in environmental biogeochemistry, plant-soil interactions, and circular economy approaches to address fundamental and applied questions in biochar and nanomaterial science.

The relationships among these authors extend beyond direct co-authorship to reveal a cohesive research community with converging interests. Also, Faizan, M. (India) collaborates extensively with Rajput, V.D. (Russia), connecting the South Asian agricultural nanotechnology network with the Eastern European soil science community. Furthermore, the Canadian cluster (Brar, Surampalli, Verma) and the Polish group (Oleszczuk, Raczkiewicz) are indirectly linked through shared co-authors such as Pan, B. and Xing, B., illustrating a web of cross-continental scientific exchange. The high h-index values of senior authors like Xing (150), Ok (174), Vithanage (90), Brar (82), and Surampalli (71) provide a strong foundational impact that elevates the visibility and credibility of their co-authors, particularly early-career researchers such as Raczkiewicz and Naghdi. This intergenerational collaboration ensures the sustained growth and intellectual diversity of the field.

The field of nano-biochar research is shaped by a diverse array of academic institutions and research centres, with significant contributions emerging from Egypt, China, Pakistan, Saudi Arabia, Russia, and Sri Lanka. An analysis of affiliation data shows that institutions with strong foundations in agricultural sciences, environmental chemistry, and materials science are at the forefront of this field. Among the 17 institutions that have published seven or more nano-biochar articles, a clear pattern of regional collaboration and disciplinary specialization emerges. Egyptian institutions dominate the top tier of contributors. Alexandria University leads with 18 nano-biochar publications, driven largely by the prolific work of Mahmoud, M.E. within its Faculty of Science. The university's strengths in chemistry, agricultural and biological sciences, and environmental science provide a robust foundation for nano-biochar research focused on adsorption, wastewater treatment, and nanocomposite development. Tanta University follows closely, supported by its Faculty of Agriculture and Faculty of Science. Key researchers Mahmoud, E. and Ibrahim, M. have contributed significantly to research on soil amendments, biochar, and nanomaterial applications in agriculture. The Agricultural Research Centre (7 publications), Egypt's premier government agricultural research institution, complements these university efforts with applied research on soil quality, environmental science, and crop production. Together, these three Egyptian institutions form a cohesive national network that accounts for a substantial portion of the country's nano-biochar output.

China's contribution is led by Northwest A&F University with 17 publications, depicting its specialization in agricultural and biological

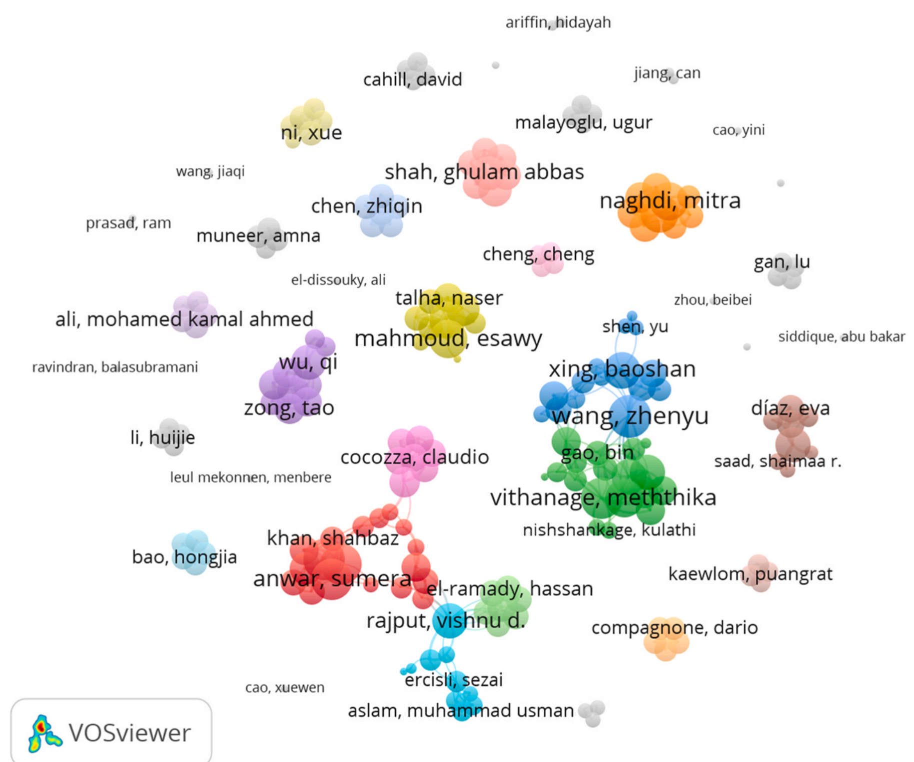


Fig. 5. Network visualization of authors with minimum of 2 documents by total link strength in nano-biochar research (2016–2025). Node size represents the number of publications, link thickness represents co-authorship strength, and colours represent collaborative clusters generated by the VOSviewer algorithm.

sciences, environmental science, and biochemistry. The university's focus on sustainable agriculture and soil health aligns closely with nano-biochar applications in crop production and environmental remediation. Jiangnan University (8 publications) contributes through its strengths in engineering, chemistry, and materials science, with researcher Wang, Z. playing a key role. Both institutions operate within China's broader research ecosystem supported by the Ministry of Education (14 publications) and the Ministry of Agriculture (9 publications). These government bodies oversee extensive research networks and funding programs, including the National Natural Science Foundation of China and the National Key Research and Development Program, which have been instrumental in advancing nano-biochar research across Chinese universities and research centres. Pakistan emerges as a significant contributor through three institutions. The University of Lahore (11 publications) and the University of Agriculture, Faisalabad (9 publications) bring expertise in agricultural and biological sciences, environmental science, and materials science. Government College Women University Faisalabad (9 publications) stands out as a key hub for nano-biochar research, with author Anwar, S. contributing seven publications focused on phytoremediation, plant physiology, and heavy metal stress. These Pakistani institutions demonstrate strong national collaboration networks and a shared focus on applying nano-biochar technologies to address agricultural and environmental challenges.

Saudi Arabia's contribution is centered on King Saud University. The university's extensive research infrastructure in chemistry, materials science, and environmental science supports nano-biochar investigations, while its funding mechanisms, including the Deanship of Scientific Research, have facilitated numerous studies in collaboration with Egyptian and Pakistani partners. King Abdulaziz University adds 7 publications, further consolidating Saudi Arabia's role as a regional leader in environmental nanotechnology research. Rounding out the top institutions are Southern Federal University in Russia (7 publications), where Rajput, V.D. leads research on nanotechnology in agriculture and soil health, and the University of Sri Jayewardenepura in Sri Lanka (7 publications), where Vithanage, M. conducts work on environmental remediation, biochar, and emerging contaminants. These institutions, though geographically distant, are connected through collaborative networks that link researchers across Asia, Europe, and the Middle East.

The country collaboration network (Fig. 6) shows both the productivity and interconnections of research efforts in nano-biochar. A total of 58 countries contributed to the field, with 41, 31, 24, and 18 countries publishing at least 2, 3, 4, and 5 documents, respectively, indicating a moderately broad but uneven distribution of research activity. China ranks as the leading contributor, with 112 publications and 4505 citations, alongside the highest total link strength (TLS) of 127, showing its central role in both research output and international collaboration. China's dominance in nano-biochar research can be attributed to a combination of structural, environmental, and policy-related factors. First, China has made investments in research and development over the past two decades, particularly in environmental materials and sustainable technologies, which has significantly increased its scientific output. Second, the country faces pressing environmental challenges, including soil contamination, industrial wastewater discharge, and agricultural sustainability issues, all of which align with the core applications of nano-biochar such as pollutant removal and soil remediation. These challenges have driven strong national interest in cost-effective and scalable solutions based on biomass-derived materials. In addition, China benefits from abundant agricultural residues, which serve as low-cost feedstocks for nano-biochar production, thereby supporting extensive experimental research. Government policies promoting waste valorization, carbon neutrality, and circular economy practices have also encouraged the development of nano-biochar-based technologies. Furthermore, the presence of well-established research institutions and extensive international collaboration networks enhances both the visibility and impact of Chinese publications in this field.

In the network map, China occupies a highly connected position, linking extensively with countries such as Australia, the United States, and Pakistan. India follows with 59 publications and 2477 citations, showing strong productivity and a well-developed collaboration network (TLS = 87), particularly with countries in the Middle East and

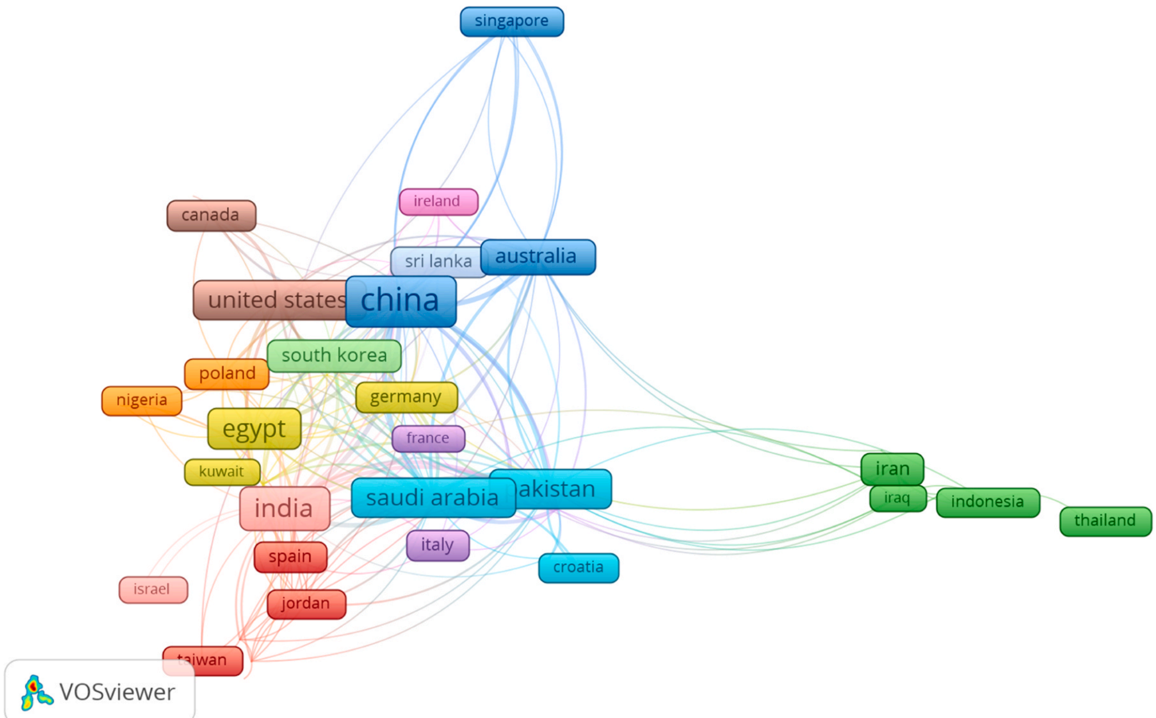


Fig. 6. Bibliometric knowledge map of country-level collaboration network in nano-biochar research based on co-authorship analysis. Node size represents the number of publications, link thickness represents co-authorship strength, and colours represent collaborative clusters generated by the VOSviewer algorithm.

Europe. Egypt (40 publications, 1011 citations) and Saudi Arabia (32 publications, 776 citations) are major contributors from the Middle East and North Africa region. Saudi Arabia shows a high total link strength (91), indicating extensive collaboration despite having fewer publications than India. The United States, with 32 publications and 2631 citations, demonstrates strong citation impact, although its total link strength (50) indicates a comparatively moderate level of collaboration within this research area. Pakistan (30 publications, TLS = 69) also plays an important collaborative role, acting as a link between Asian and Middle Eastern research clusters, as seen in the visualization. Australia (18 publications, TLS = 48) contributes to connecting Asian research hubs, particularly China and Southeast Asian countries such as Indonesia and Thailand.

European countries show moderate contributions with a distributed presence across the network. Turkey (16 publications), Poland (9), the United Kingdom (9), Italy (9), and Germany (7) form smaller collaborative clusters or maintain connections with major hubs such as China and Saudi Arabia. South Korea (14 publications, 1765 citations) demonstrates high citation impact relative to its publication count, indicating strong research influence. Emerging contributors such as Iran (10 publications), Sri Lanka (7), Jordan (4), and Nigeria (as observed in the network visualization) appear toward the periphery, indicating growing but still limited participation. These countries tend to form regionally focused collaborations, particularly within Asia and the Middle East, with fewer direct connections to the major hubs.

7. Subject area and disciplinary distribution

The interdisciplinary nature of nano-biochar research is shown in the range of subject areas contributing to the field. Analysis of Scopus subject category data shows that nano-biochar research spans the natural sciences, engineering, and life sciences, with a clear concentration in environmentally oriented disciplines. Environmental Science ranks as the dominant subject area, accounting for 145 publications (55.6% of total documents). This representation confirms that nano-biochar research is primarily situated within environmental contexts, with emphasis on pollution control, remediation technologies, and ecosystem applications. The prominence of this category shows the field's foundational concern with addressing environmental contamination through carbon-based materials. Agricultural and Biological Sciences follows with 63 publications (24.1%), indicating the significant role of nano-biochar in soil health management, crop production, and sustainable agriculture. This subject area captures research on plant growth responses, soil amendments, and the interactions between nano-biochar and biological systems.

Materials Science (55 publications, 21.1%) and Chemistry (45 publications, 17.2%) represent the material-centric dimensions of the field. These categories encompass research on synthesis methods, surface functionalization, characterization techniques, and the physicochemical properties that govern nano-biochar performance. Chemical Engineering (48 publications, 18.4%) and Engineering (30 publications, 11.5%) further emphasize the process-oriented aspects, including reactor design, scale-up considerations, and treatment system optimization. Energy (26 publications, 10.0%) captures research on thermochemical conversion conditions, energy recovery from biomass, and applications of nano-biochar in energy storage and conversion devices. Biochemistry, Genetics and Molecular Biology (16 publications, 6.1%) and Physics and Astronomy (15 publications, 5.7%) represent more specialized contributions, including mechanistic studies at the molecular level and investigations of nanoscale physical properties.

Smaller contributions appear across Medicine (12 publications), Multidisciplinary (10 publications), and Pharmacology, Toxicology and Pharmaceutics (10 publications), indicating emerging intersections with biomedical applications and toxicological assessments. The presence of Business, Management and Accounting (7 publications), Social Sciences (6 publications), and Earth and Planetary Sciences (6 publications) shows the broadening scope of nano-biochar research to include sustainability assessments, economic considerations, and geochemical interactions. Minor contributions from Immunology and Microbiology (4 publications), Computer Science (3 publications), and single publications in Health Professions, Mathematics, Psychology, and Veterinary complete the disciplinary scope. The distribution of subject areas shows that nano-biochar research is fundamentally interdisciplinary, with Environmental Science serving as the central hub connecting material development, chemical characterization, agricultural application, and engineering optimization. The concentration of publications in Environmental Science, Agricultural and Biological Sciences, and Materials Science confirms that the field's primary orientation remains at the intersection of environmental remediation, sustainable agriculture, and advanced material design.

8. Emerging trends and research frontiers

Nano-biochar research is shifting from descriptive characterization to design-driven engineering. Early studies focused on understanding surface chemistry and adsorption performance. Current research emphasizes how to control nanoscale structure for predictable performance. Process optimization is becoming data-centric, with greater use of modelling, simulation, and parameter integration. Future studies should standardize production protocols that define relationships between feedstock type, temperature, and surface reactivity. Such uniformity will improve reproducibility and allow comparative analysis across laboratories. There is a growing focus on functionalization strategies. Researchers are moving beyond unmodified biochar toward chemically tailored surfaces that target specific pollutants or reactions. Oxidation, sulphonation, metal doping, and polymer coating are now routine approaches. These methods increase surface charge, hydrophilicity, and catalytic efficiency. Future research should expand toward multi-functional materials that combine adsorption, redox activity, and sensing in a single structure. Studies should also quantify how modification affects stability, toxicity, and reusability under real environmental conditions.

Hybridization with other nanomaterials is another clear direction. Nano-biochar is being combined with graphene, silica, zeolite, and metal oxides to improve mechanical strength and conductivity. Iron-based hybrids dominate due to their redox versatility, but diversification is underway. Copper, manganese, and titanium systems show promise for specific catalytic or antimicrobial purposes. Research should now address the long-term stability of these hybrids in complex matrices such as wastewater and soil. Understanding interfacial interactions between biochar and non-carbon additives will define their reliability for continuous operation. A strong trend toward quantitative modelling is evident. The frequent study of adsorption kinetics, isotherms, and thermodynamics shows an ongoing effort to predict behaviour mathematically. Yet many models remain empirical. The next phase should integrate mechanistic modelling with computational chemistry and molecular dynamics. Predictive frameworks must link electronic structure with macroscopic adsorption or catalytic outcomes. This shift will allow rapid material screening and reduce experimental redundancy.

Data-driven analytics are emerging as a decisive tool. Machine learning and artificial intelligence are being introduced to predict synthesis outcomes, optimize reaction conditions, and correlate material descriptors with performance indicators. The field is moving toward predictive synthesis rather than trial-and-error production. Creating open-access datasets that combine structural, physicochemical, and performance data will accelerate this transition. Such databases will also facilitate the creation of digital twins for process simulation and optimization. Sustainability is becoming a measurable objective. Earlier studies focused on laboratory efficacy, while current research assesses energy consumption, recyclability, and lifecycle impact. Feedstock diversification supports this shift, with emphasis on agricultural and municipal wastes as precursors. The goal is to achieve low-cost, low-emission synthesis that supports circular economy principles. Future studies should incorporate energy balances, carbon footprint analysis, and post-use recovery rates into performance evaluation. The development of biochar certification standards will depend on such quantitative metrics. Toxicological evaluation represents a rising research frontier. The term toxicity appears frequently but lacks systematic treatment. Studies must now address how nanoparticle size, surface charge, and composition influence eco-toxicity. Standardized toxicity assays using aquatic and terrestrial organisms are needed. Research should also measure nanoparticle persistence, aggregation behaviour, and transformation under realistic pH and ionic conditions. Risk assessment models must be developed to guide regulatory frameworks and ensure environmental safety during large-scale deployment.

The agricultural dimension of nano-biochar research is advancing toward precision control. Early work focused on soil fertility improvement, but the new emphasis lies in soil-microbe-nano-biochar interactions. Studies now measure enzymatic responses, microbial diversity, and nutrient mobility. The next step involves real-time monitoring of soil processes using sensors and imaging tools. This will provide data for modelling nutrient cycling and water retention. Long-term field experiments are required to establish durability and reproducibility under variable climate and soil conditions. In environmental applications, the direction is toward multi-pollutant systems. Previous studies targeted single contaminants under controlled conditions. Research now addresses mixtures of organic and inorganic pollutants. Understanding competitive adsorption, reaction selectivity, and secondary by-product formation is essential. Studies should also explore dynamic flow conditions, scaling from batch experiments to continuous treatment systems. This approach will bridge laboratory findings with industrial feasibility. Energy applications are gaining momentum. Nano-biochar is entering research on electrodes for batteries and supercapacitors. Its conductivity, porosity, and surface functionality provide a foundation for energy storage and conversion. Recent work demonstrates high charge transfer efficiency and structural stability under cycling. Expanding this research toward hybrid electrodes that integrate metal oxides or conductive polymers will broaden its utility. Studies should focus on improving energy density while maintaining sustainability in raw material sourcing.

Integration with catalysis is accelerating. Nano-biochar-based catalysts are being applied in advanced oxidation and reduction processes. The emphasis is on selective degradation of persistent organic pollutants. Redox-active composites combining iron, cobalt, or nickel with biochar have shown high catalytic turnover. Future research should aim to design recyclable catalytic systems that function under mild conditions. Integration with solar-driven or electrochemical processes will make nano-biochar catalysts more energy-efficient and adaptable to decentralized treatment systems. There is increasing interest in the structural evolution of nano-biochar under operational conditions. Prolonged exposure to high temperature, radiation, or chemical reagents can alter morphology and surface chemistry. Understanding degradation pathways will determine long-term performance. Studies should employ in-situ characterization to track structural and functional changes during adsorption or catalysis. This will improve understanding of reusability limits and regeneration requirements.

Collaboration networks are expanding rapidly. Bibliometric data show strong contributions from Asia, followed by Europe and North America, with emerging participation from Africa and South America. The future of the field depends on cross-continental collaboration linking synthesis, modelling, and field validation. Establishing shared experimental protocols and centralized data repositories will promote comparability and reproducibility. International partnerships should target thematic gaps such as toxicity, scalability, and standardization rather than duplicate well-studied themes.

Methodological innovation is another visible trend. Researchers are adopting micro-reactor systems, green solvents, and continuous-flow setups for nano-biochar synthesis. Such methods improve control over particle size and surface morphology while reducing emissions. The next challenge is to develop modular systems that integrate synthesis, activation, and application within a single process chain. Automation and real-time monitoring will enhance consistency and process transparency. Standardization is becoming a central concern. The absence of uniform terminology and metrics complicates data comparison.

Establishing standards for pore volume, surface charge density, and carbon crystallinity will improve scientific coherence. Benchmark materials with known physicochemical profiles should be developed as references for inter-laboratory comparison. These standards will also support industrial certification and facilitate policy adoption. Future research should link nano-biochar design to measurable performance indicators. Studies should quantify adsorption efficiency per unit surface area, energy input per gram of product, and regeneration cycles before performance decline. Such metrics will translate laboratory findings into engineering benchmarks. The field will advance by combining experimental precision, computational insight, and sustainability metrics within unified research frameworks. Nano-biochar science is now entering a stage of consolidation and refinement. The discipline has moved from discovery to targeted design, from single-parameter optimization to system-level integration, and from isolated experiments to collaborative standardization. Progress will depend on developing predictive synthesis models, standardized safety protocols, and scalable applications that combine environmental remediation with material innovation. These directions define the next frontier of nano-biochar research between scientific advancement and sustainable implementation.

9. Conclusion

This study presents a bibliometric analysis of nano-biochar research, drawing on a dataset of 261 peer-reviewed documents retrieved from the Scopus database to assess publication trends, identify leading contributors, and analyze emerging research themes over the period 2016–2025. Annual publications increased from a single paper in 2016–75 in 2025. Correspondingly, annual citations rose from zero in 2016–2746 in 2025. Research output is concentrated in a defined set of journals, with the top 30 most productive journals accounting for 59.4% of all publications. The leading journals are Science of the Total Environment (16 publications), followed by Journal of Cleaner Production, Environmental Science: Nano, Environmental Research, and Environmental Pollution (each with 7 publications). Funding analysis revealed strong support from national and international agencies, with the National Natural Science Foundation of China supporting the most studies (58), while contributions from Canada, Poland, Saudi Arabia, Egypt, and other nations support a growing research network. Keyword co-occurrence and clustering analysis identified six thematic clusters. Research leadership is concentrated among prolific authors and institutions, primarily in China, with collaborative networks extending to India, the United States, Saudi Arabia, Pakistan, Egypt, and Russia. Recent publications indicate a growing shift toward hybrid materials, sustainability assessment, toxicity evaluation, and predictive modelling approaches. The bibliometric patterns show that nano-biochar research has evolved from descriptive material characterization toward performance-driven engineering targeting multi-functionality, safety, and scalability. This study provides a benchmark for understanding how collaboration, thematic focus, and methodological precision shape nano-biochar research. The field now stands at a transition point where synthesis, function, and sustainability must align to deliver measurable environmental and technological impact.

Despite its contributions, this study has several limitations that should be acknowledged. First, the exclusive reliance on the Scopus database, while justified by its broad coverage, introduces indexing biases and may underrepresent research published in regional journals or in languages other than English. Second, the restriction to English-language publications, while necessary for consistent analysis, excludes potentially valuable non-English research. Third, the search strategy, despite iterative refinement, may have inadvertently excluded relevant documents using alternative terminology not captured by the selected keywords. Fourth, author and institutional name disambiguation remains challenging in bibliometric analyses, and some residual errors may persist despite manual standardization. Fifth, the manual screening process, while guided by explicit decision rules, involves subjective judgments that may affect the final dataset composition. These limitations suggest that the findings should be interpreted as representative of nano-biochar research as indexed in Scopus, rather than an exhaustive account of all global research activity.

The patterns observed in this analysis suggest several implications for future research and policy. For researchers, the identification of six thematic clusters provides a roadmap for positioning new contributions within the existing intellectual structure, with opportunities for cross-cluster integration (e.g., combining material synthesis advances with biological interaction assessments). For funding agencies, the concentration of research in adsorption and remediation themes, contrasted with the relative underdevelopment of energy applications and toxicity evaluations, highlights areas where strategic investment could accelerate field development. For international collaboration, the network analysis reveals both established partnerships (e.g., China-United States-South Korea) and emerging contributors (e.g., Nigeria, Jordan) that represent opportunities for capacity building and knowledge exchange. Future bibliometric studies in this field would benefit from incorporating multiple databases (e.g., Web of Science, Dimensions) to enable cross-validation, applying more advanced analytical techniques such as natural language processing for deeper thematic analysis, and extending temporal coverage to capture ongoing developments.

CRediT authorship contribution statement

Kingsley O. Iwuozor: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hussein Kehinde Okoro:** Conceptualization, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Adewale George Adeniyi:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Consent for publication

The authors have unanimously decided that this manuscript be sent for possible publication.

Funding

This work received no external funding.

Declaration of Competing Interest

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

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