



Mapping Global Collaboration and Research Trends in Nanocellulose: A Bibliometric and Text Mining Analysis

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ABSTRACT

Nanocellulose has emerged as a promising biomaterial with broad applications across sustainable packaging, biomedical engineering, and environmental remediation. Despite increasing global interest, a comprehensive understanding of the collaborative dynamics and evolving research directions in this field remains limited. This study aims to map the global research landscape of nanocellulose from 2021 to 2025 through an integrative bibliometric and text mining approach. A total of 2,971 scientific articles were retrieved from the Scopus database using a targeted query focused on nanocellulose-related keywords within the materials science domain. The metadata was analyzed using VOSviewer to visualize co-authorship networks, keyword co-occurrence, citation linkages, and bibliographic coupling. Complementary text analysis, including topic modeling via Latent Dirichlet Allocation (LDA), was conducted using Python libraries such as NLTK, spaCy, and Gensim. The results reveal China as the leading country in terms of research output, institutional collaboration, and funding, followed by India and the United States. Key thematic clusters center around biomedical applications, composite development, and water treatment. Highly cited authors and organizations are concentrated in specialized pulp and paper research institutes. This study not only delineates the structure and trajectory of global nanocellulose research but also highlights emerging areas and collaboration patterns. The findings can guide future research investments, inform policy decisions, and foster strategic academic partnerships in the rapidly evolving field of cellulose-based nanomaterials.

Keywords: nanocellulose, bibliometric, text mining, scopus, python

INTRODUCTION

Nanocellulose has emerged as a transformative material in recent years, offering a unique combination of biodegradability, high mechanical strength, nanoscale dimensions, and renewability. Derived primarily from plant-based cellulose, this material aligns strongly with the global pursuit of sustainable and eco-friendly innovations, particularly in the context of reducing dependency on fossil-based and non-renewable resources [1]. Its versatility has enabled nanocellulose to be explored across a wide range of industrial applications. Notably, it has been utilized in biomedical devices, food packaging, wastewater treatment, electronics, composite materials, and energy storage systems. These applications demonstrate its potential to serve as a platform technology in multiple sectors, especially within the growing domain of green materials science [2], [3]. In parallel with the increasing application potential, academic interest in nanocellulose has also surged. Scientific publications on the topic have multiplied in recent years, with contributions from researchers worldwide. However, this expansion has led to a fragmented understanding of the underlying research trends, collaboration networks,

and thematic orientations that define the field [4]. One key gap in the current body of knowledge is the lack of a systematic synthesis of global collaboration patterns and how they influence the development of research themes in nanocellulose. While certain countries and institutions have shown consistent leadership, there remains limited analysis of how these actors interconnect and contribute to the knowledge ecosystem in a coherent, data-driven manner [5], [6].

Furthermore, the role of funding agencies, leading authors, and dominant journals in shaping the field's trajectory is not yet fully understood. Bibliometric evidence can shed light on such dynamics, offering empirical insights into which players and platforms are driving scientific advancement [7]. Another underexplored area is the evolution of research topics in nanocellulose over time. Text mining and topic modeling techniques, when applied to publication metadata, can help surface emerging research frontiers, identify shifts in focus, and reveal latent structures that are not immediately visible through traditional literature reviews [8], [9]. In response to these gaps, this study employs a bibliometric and text analysis approach using Scopus metadata from 2021 to 2025. Tools such

as VOSviewer and Python (with NLP libraries including NLTK, spaCy, and Gensim) are used to analyze and visualize patterns of co-authorship, co-occurrence, citations, and thematic clustering [10]. By combining these methods, the present study seeks to provide a comprehensive overview of the global research landscape on nanocellulose, highlighting influential contributors, collaboration networks, topical trends, and

funding patterns. The results aim to support researchers, institutions, and policy-makers in making informed decisions and fostering more effective scientific collaboration and innovation in this critical field [11], [12]. In Figure 1 we can see Various nanocellulose products and their microscopic morphology.

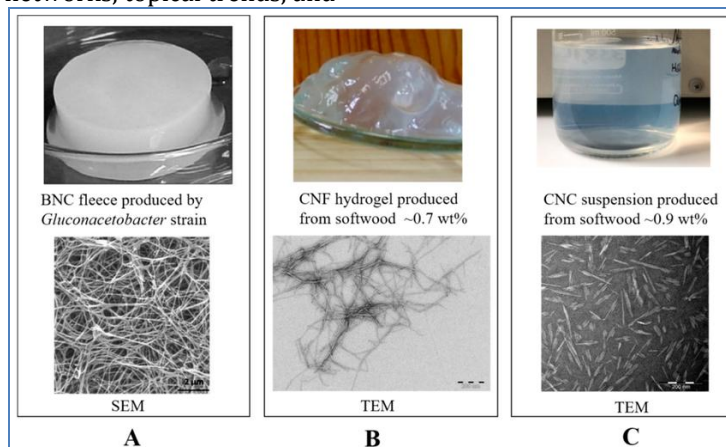


Figure 1. Various nanocellulose products and their microscopic morphology [13], [14]

RESEARCH METHODS

This research is a descriptive quantitative study using bibliometric and text analysis approaches, aimed at mapping the development of research on cellulose-based nanomaterials within the field of materials science. The dataset was obtained from the Scopus database using a specific search query [11]: TITLE-ABS-KEY (nano AND cellulose) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (SUBJAREA , "MATE")) AND (LIMIT-TO (EXACTKEYWORD , "Cellulose") OR LIMIT-TO (EXACTKEYWORD , "Nanocellulose") OR LIMIT-TO (EXACTKEYWORD , "Nano-cellulose"))

This query was designed to filter scientific articles relevant to the topic of nano and cellulose within the subject area of materials science, limiting the publication years to 2021–2025, and retrieving only articles that explicitly include the keywords “Cellulose,” “Nanocellulose,” or “Nano-cellulose.” The collected metadata includes titles, abstracts, authors, affiliations, publication years, keywords, and journal sources. Bibliometric analysis was conducted using VOSviewer to visualize co-authorship, co-occurrence, and citation networks. Subsequently, text analysis was performed using Python with the NLTK, spaCy, and Gensim libraries for data preprocessing and topic extraction via Latent Dirichlet Allocation (LDA). Keyword trend visualizations were generated using WordCloud and matplotlib, and insights from Scopus-AI were utilized to synthesize qualitative findings and enrich interpretation. Validity is ensured through the use of reliable data sources and triangulation of results across multiple analytical tools [15], [16]. The dataset comprises 46 columns containing comprehensive information such as authorship, institutional affiliations, source journals, abstracts, keywords, funding agencies,

document types, and citation counts. The data were initially collected to assess completeness and identify null or sparse columns. Variables with substantial missing data (e.g., Molecular Sequence Numbers, Tradenames) were excluded from deeper analysis to ensure consistency and integrity [5]. Preprocessing of textual data involved the use of Python with NLTK and spaCy libraries for tokenization, stopword removal, lemmatization, and standardization. Special characters, punctuation, and redundant terms were removed to normalize the content. This step ensured that the textual input for topic modeling and keyword analysis was semantically consistent and analytically valid [14], [17].

VOSviewer software was used to perform co-authorship, institutional collaboration, country-level mapping, citation analysis, and co-occurrence of keywords. Visualization maps generated using VOSviewer revealed clusters of research communities, thematic focus areas, and citation impacts, which were interpreted in the context of nanocellulose research networks [18]. Latent Dirichlet Allocation (LDA), implemented in the Gensim library, was used to extract latent topics from article abstracts and titles. WordCloud and matplotlib were used to visualize frequently occurring terms, which provided qualitative insights into emerging research directions. This text mining approach complements the quantitative bibliometric findings [19]. A TF-IDF-based article similarity matrix was constructed to examine thematic overlap between publications. Collaboration networks among authors were constructed using Scopus author IDs, which were then visualized to identify prolific co-authorship clusters. This revealed structural insights into the collaborative fabric of the field [20]. To ensure robustness, multiple analytical tools were used and triangulated: Scopus built-in analytics for general trend confirmation, VOSviewer for network mapping, and

Python for advanced NLP-based insights. The consistency of results across tools served as a validity

check. A simplified methodological workflow is illustrated in Figure 2 [21].

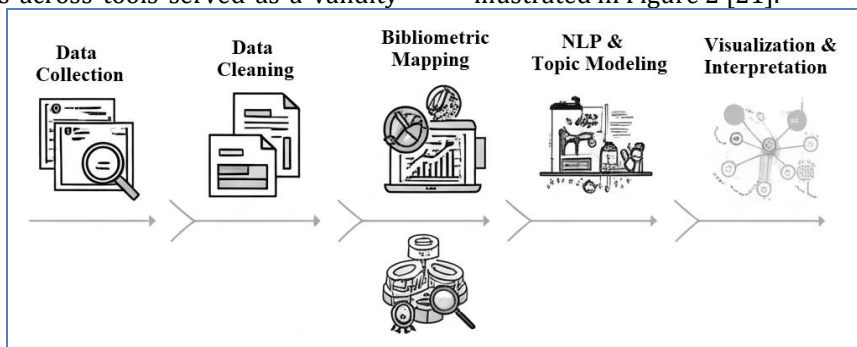


Figure 2. Methodological workflow [3]

RESULT AND DISCUSSION

This section presents the findings and analysis derived from all stages described in Methodology. The study results begin with an initial exploration of the dataset to extract basic statistical insights, followed by a review of Scopus's built-in visualization tools to observe general trends. Further in-depth analysis was conducted using VOSviewer for bibliometric mapping and Python for customized data processing. Machine learning

techniques were then applied to the metadata to discover latent patterns and research directions. To complement these methods, generative AI tools such as Scopus-AI and other consensus-driven platforms were employed to enhance the interpretation of findings. The results of these comprehensive study stages are presented and discussed in the following subsections [6]. In Table 1 we can see a glimpse of the Initial information from the dataset.

Table 1. Initial information from the dataset [22]

Attribute	Non-Null Count	Data Type
Authors	2,970	Object
Author full names	2,970	Object
Author(s) ID	2,970	Object
Title	2,971	Object
Year	2,971	Integer
Source title	2,971	Object
Volume	2,818	Object
Issue	1,823	Object
Art. No.	1,451	Object
Page start	1,449	Object
Page end	1,448	Object
Page count	1,449	Float
Cited by	2,971	Integer
DOI	2,944	Object
Link	2,971	Object
Affiliations	2,970	Object
Authors with affiliations	2,970	Object
Abstract	2,971	Object
Author Keywords	2,671	Object
Index Keywords	2,896	Object
Molecular Sequence Numbers	0	Float
Chemicals/CAS	602	Object
Tradenames	25	Object
Manufacturers	22	Object
Funding Details	2,453	Object
Funding Texts	2,436	Object
References	2,964	Object
Correspondence Address	2,855	Object
Editors	48	Object
Publisher	2,967	Object
Sponsors	28	Object
Conference name	83	Object
Conference date	83	Object
Conference location	83	Object
Conference code	83	Float

Attribute	Non-Null Count	Data Type
ISSN	2,909	Object
ISBN	75	Object
CODEN	1,756	Object
PubMed ID	699	Float
Language of Original Document	2,971	Object
Abbreviated Source Title	2,971	Object
Document Type	2,971	Object
Publication Stage	2,971	Object
Open Access	978	Object
Source	2,971	Object
EID	2,971	Object

The initial information extracted from the dataset provides a foundational overview of the research landscape related to cellulose-based nanomaterials. This includes basic descriptive statistics such as the number of publications per year, the most prolific authors, leading source journals, and contributing countries. These metrics offer insight into the growth trends and geographic distribution of research activity, highlighting influential contributors and institutions. Additionally, preliminary patterns in citation frequency and keyword usage begin to reveal emerging themes and the evolving focus areas within the field, serving as a valuable starting point for more in-depth bibliometric and thematic analysis [20]. The dataset consists of 2971 entries, each characterized by 46 columns of varying data types.

The columns encompass a range of information, including author details (names, IDs, affiliations), publication metadata (title, year, source, volume, issue, pages), citation counts, digital identifiers (DOI, Link), content-related information (abstract, keywords), funding details, references, and publication specifics (publisher, ISSN, language, document type, open access status). While most columns have complete or near-complete data, some columns like 'Art. No.', 'Page start', 'Page end', 'Molecular Sequence Numbers', 'Chemicals/CAS', 'Tradenames', 'Manufacturers', 'Editors', 'Sponsors', 'Conference details', 'ISBN', 'CODEN', and 'PubMed ID' have substantial missing

data, with 'Molecular Sequence Numbers' being entirely empty. The dataset appears to be comprehensive, covering various aspects of scholarly publications, with the number of null values varying across columns [8]. Table 1, "Dataset Information," reveals a rich and varied structure underlying the dataset, encompassing 2971 entries and 46 columns designed to capture a wide array of scholarly publication details. These 46 columns can be categorized into three primary data types: float64 (4 columns) for precise numerical measurements, int64 (2 columns) for integer-based counts and identifiers, and object (40 columns) for textual and categorical information.

The dataset masterfully blends quantitative metrics with qualitative context, including textual information such as author names, article titles, abstracts, and keywords, alongside numerical data like publication years and citation counts. Despite its comprehensive nature, certain columns exhibit varying degrees of missing data, highlighting potential avenues for data imputation or targeted analysis, while others such as "Molecular Sequence Numbers" remain entirely devoid of information, suggesting they might be excluded from further exploration. This meticulously curated collection promises fertile ground for insightful analysis into publication trends, collaborative networks, and the impact of scholarly research [23].

Table 2. Publication Year Distribution [24]

Publication Year	Count
2021	434
2022	751
2023	732
2024	752
2025	302
Total	2,971

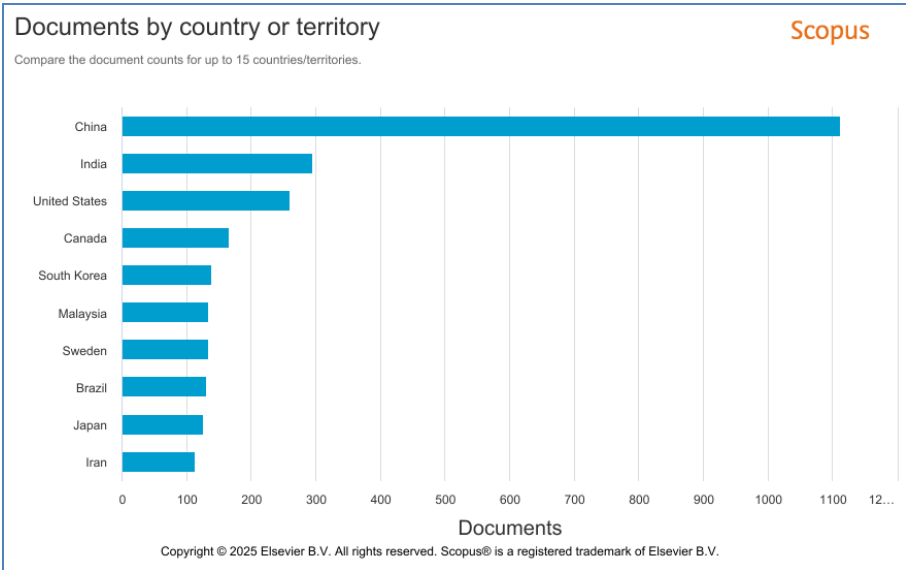
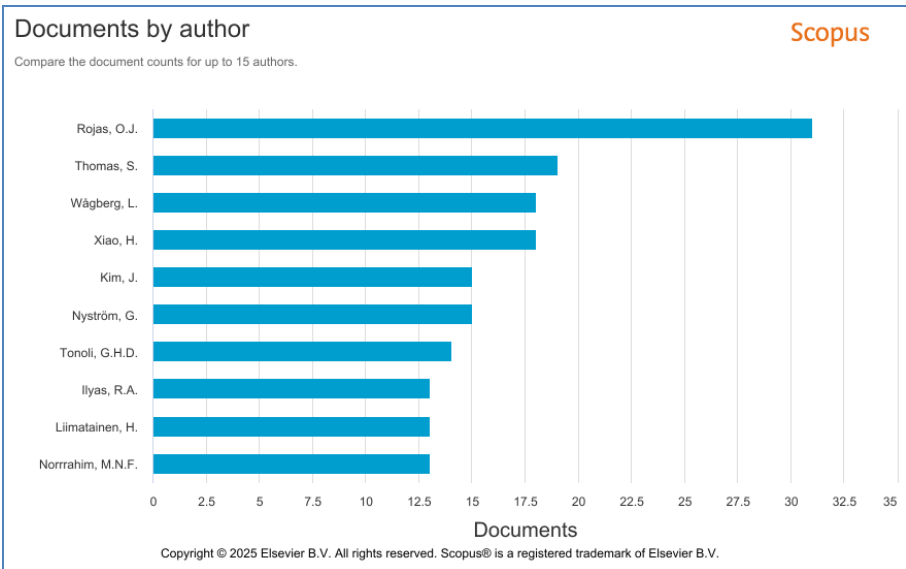
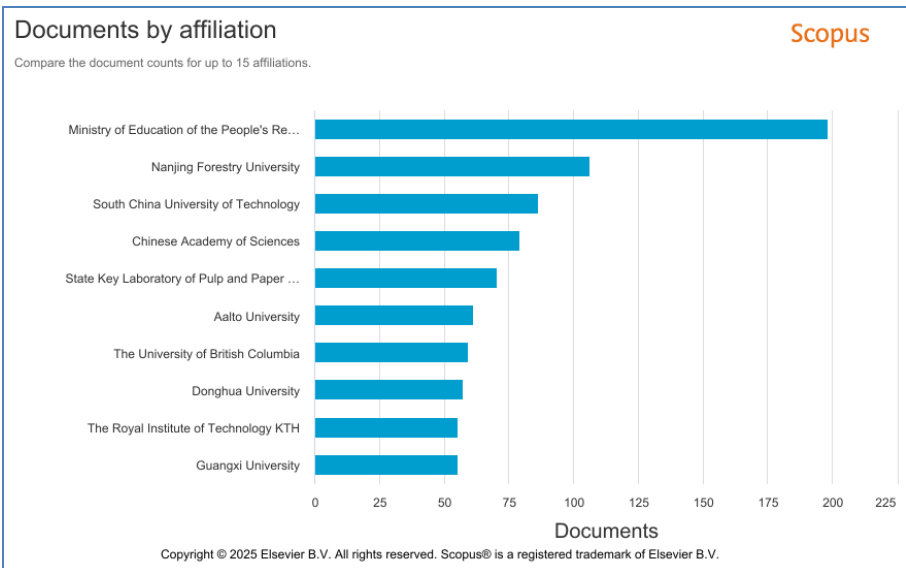
The table titled Publication Year Distribution shows the number of publications per year from 2021 to 2025. In 2021, there were 434 publications. The number of publications increased to 751 in 2022, then slightly decreased to 732 in 2023. The number of publications peaked at 752 in 2024 before sharply declining to 302 in 2025. Overall, the table indicates a peak in publication numbers between 2022 and 2024, with a significant decrease in 2025 compared to previous years [25]. The default built-in visualization tools available on the Scopus web platform offer a quick and accessible means

for researchers to gain initial insights into publication data. These tools, which include visual representations such as bar charts, line graphs, and network diagrams, are designed to illustrate trends in publication volume, citation counts, author collaborations, and keyword co-occurrences. Although relatively simple and limited in customization compared to specialized bibliometric software, these visualizations serve as a valuable starting point for understanding the structure and dynamics of a field of research. They help users identify prominent authors, active journals, and emerging topics

with minimal technical effort, making them especially useful for preliminary exploration and decision-making

in the early stages of academic research [26]. In Table 3 we can see some of the Scopus built-in visualizations.

Table 3. Scopus Built-in Visualizations [5]

Category	Visualization
Scopus-Analyze-Country	Documents by country or territory Compare the document counts for up to 15 countries/territories.  Documents Copyright © 2025 Elsevier B.V. All rights reserved. Scopus® is a registered trademark of Elsevier B.V.
Scopus-Analyze-Author	Documents by author Compare the document counts for up to 15 authors.  Documents Copyright © 2025 Elsevier B.V. All rights reserved. Scopus® is a registered trademark of Elsevier B.V.
Scopus-Analyze-Affiliation	Documents by affiliation Compare the document counts for up to 15 affiliations.  Documents Copyright © 2025 Elsevier B.V. All rights reserved. Scopus® is a registered trademark of Elsevier B.V.

The following is an interpretation of all the built-in visualizations from Scopus for the downloaded dataset, providing initial insights before conducting analysis using various tools. The Scopus database offers a compelling glimpse into the landscape of scientific research, revealing a pronounced concentration in specific disciplines. Materials Science emerges as the dominant field, commanding a substantial 45.4% of the documented research. This significant share underscores the ongoing emphasis and importance of materials-related studies in the scientific community. Following closely behind Materials Science is Chemistry, which accounts for 20.4% of the documents. Engineering and Physics contribute substantially as well, holding 11.8% and 7.5%, respectively. This distribution highlights the core areas driving scientific advancement and innovation, reflecting the current priorities and focal points of scholarly investigation. Analyzing document trends over recent years reveals intriguing dynamics. Between 2021 and 2024, sources such as Carbohydrate Polymers and Cellulose experienced a growth trajectory in document counts, indicating increasing interest and activity in these areas. However, 2025 brought a shift, with many sources

experiencing a decline, signaling potential changes in research focus or funding [10].

The financial backing of scientific research demonstrates a strong influence from Chinese institutions. The National Natural Science Foundation of China and the Ministry of Science and Technology of China emerge as the top funding sponsors, surpassing contributions from other international entities. This highlights China's growing investment and prominent role in shaping the direction of global scientific endeavors. In terms of publication types, articles overwhelmingly dominate, comprising 83.0% of the documents. Reviews serve as a significant secondary source of information, accounting for 12.0%. Geographically, China leads in the number of document contributions, reflecting its increasing prominence in the global research arena. Within the author landscape, Rojas, O.J. stands out as the most prolific contributor, while the Ministry of Education of the People's Republic of China, along with Nanjing Forestry University, are the leading affiliations. These insights provide a multi-faceted view of the data, revealing key trends, influential players, and dominant themes within the Scopus database [27].

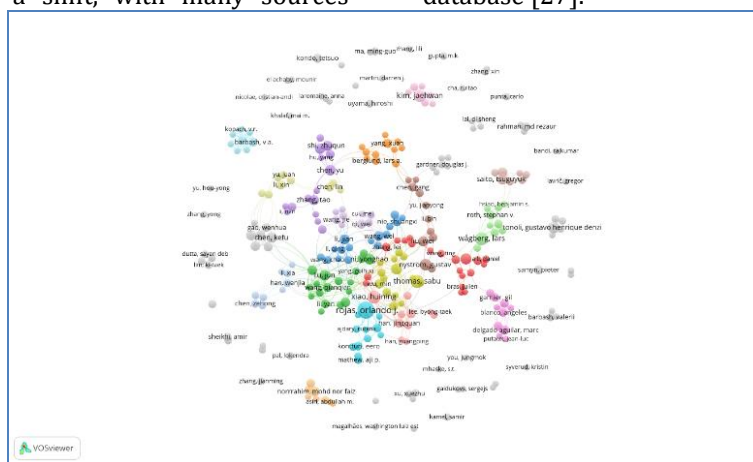


Figure 3. Co-authorship_authors [28]

The results of the study using VOSviewer revealed intricate patterns and relationships within the field of cellulose-based nanomaterials research through comprehensive bibliometric mapping. By visualizing networks of co-authorship, co-citation, and keyword co-occurrence, the analysis highlighted key researchers, influential publications, and dominant thematic clusters shaping the field. The co-authorship map identified active collaboration networks and leading research institutions, while the co-citation analysis exposed foundational works and highly cited sources that form the intellectual structure of the discipline. Meanwhile, keyword co-occurrence mapping illuminated emerging research trends, commonly explored topics, and the conceptual focus of scholarly discourse. These visual insights offer a nuanced understanding of the scientific landscape, providing valuable guidance for future research directions and strategic collaboration opportunities [29], [30]. In Figure 3, the VOSviewer map

reveals a densely interconnected landscape of authors clustered by co-citation and collaborative relationships: each colored group represents a thematic community, with red nodes—such as “samyn, pieter” and “garnier, gil”—suggesting a tightly knit research focus, while the green cluster around “xiao, huining” and “rojas, orlando j.” highlights another prominent subfield. The spatial proximity of nodes indicates frequent co-occurrence in publications, and larger nodes—like “thomas, sabu” in yellow—denote authors with higher citation impact or centrality. Peripheral gray nodes, including “sheikh, amir” and “pal, lokendra,” suggest emerging contributors or niche topics that are less integrated into the core network. Overall, visualization underscores distinct but overlapping scholarly communities and points to key thought leaders bridging multiple research themes [31].

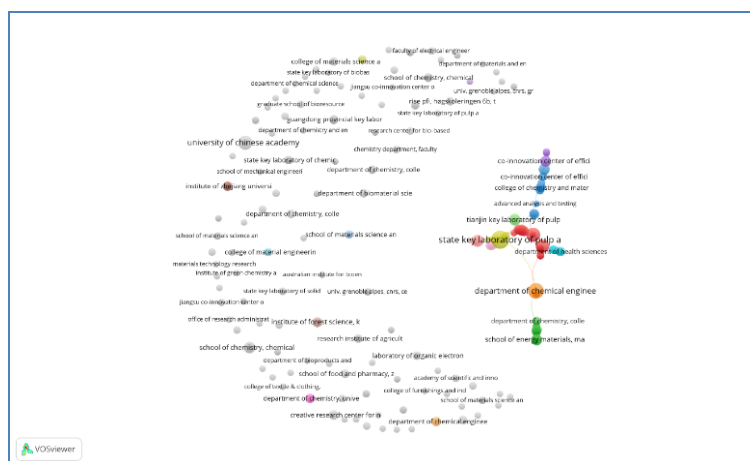


Figure 4. Co-authorsip_organizations [32]

In Figure 4, the VOSviewer visualization reveals several distinct but interlinked institutional clusters based on co-authorship and thematic focus: the red cluster centers on the “state key laboratory of pulp & paper,” indicating a strong collaborative hub in pulp science and engineering, while the adjacent orange nodes around “department of chemical engineering” highlight a related community focused on chemical processes in materials. The green cluster dominated by “school of materials science and engineering” suggests another research stream in advanced materials, and its proximity to the yellow-tinged “college of materials

science” nodes points to frequent interdisciplinary exchange. Meanwhile, the gray and purple nodes—including “university of Chinese Academy” and various “department of chemistry” labels—form peripheral groups that contribute niche expertise, indicating emerging or less densely connected collaborations. Overall, the map underscores how specialized laboratories and departments interweave through co-authorship ties to shape the broader materials and chemical sciences landscape [33].

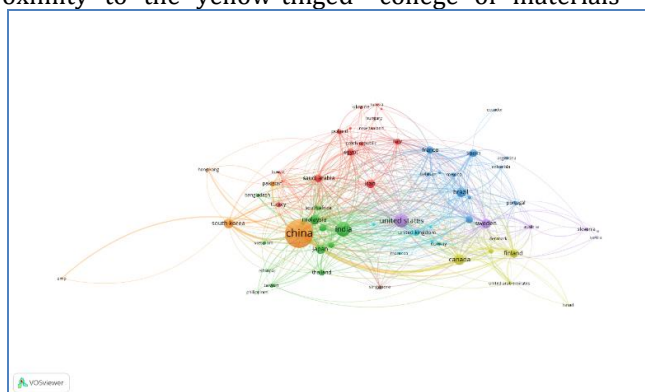


Figure 5. Co-authorship_countries [34]

In Figure 5, The VOSviewer map illustrates a global collaboration network in which countries form tightly knit yet overlapping clusters: the large orange node for China and green node for India reveal these nations as major hubs with extensive links to neighboring countries in Asia (e.g., Japan, South Korea, Vietnam), while the prominent blue node for the United States anchors a Western cluster that includes the United Kingdom, France, and Germany. Canada (yellow) sits at the interface between the North American and European groups, and smaller purple and red nodes, such as Sweden, Finland, and Iran, highlight regional subcommunities that maintain strong intra-cluster ties yet also connect outward to bridge diverse research domains. The density and thickness of connecting lines indicate the frequency of co-authorships: the thicker the line, the more prolific the bilateral collaborations, underscoring how scientific partnerships transcend geographic boundaries to form a richly interconnected global research landscape [36]. In Figure 6, The

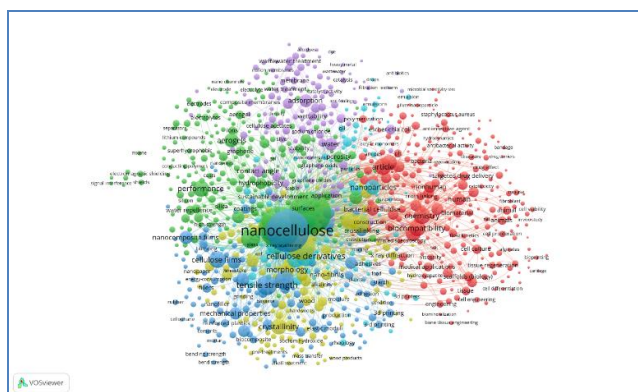


Figure 6. Co-occurrence_all keywords [35]

VOSviewer network highlights the multidisciplinary research landscape surrounding nanocellulose applications: the central green cluster, dominated by “nanocellulose” and “cellulose derivatives”, reflects fundamental studies on morphology, tensile strength, and crystallinity, while the adjacent blue nodes emphasize mechanical properties and composite film development. To the right, the red cluster concentrates on biomedical and biocompatibility topics, terms like “nanoparticles,” “drug delivery,” and “tissue engineering” reveal an expanding interest in nanocellulose for healthcare and regenerative medicine. Above, the purple grouping focuses on water treatment and adsorption processes, with keywords such as “wastewater treatment,” “adsorption,” and “antibiotics removal” indicating environmental and filtration applications. The yellow nodes interspersed among these areas, featuring “production,” “sustainable development,” and “surface modification”, underscore the shared methodological and sustainability concerns

that bridge these thematic domains, illustrating how core material properties enable diverse industrial,

environmental, and biomedical innovations [37].

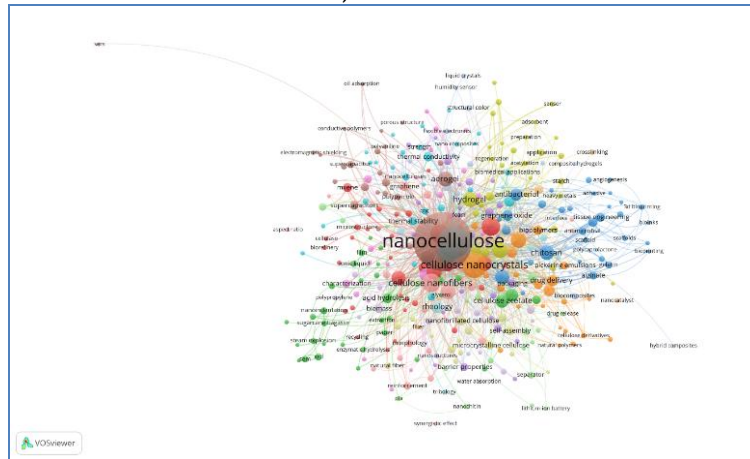


Figure 7. Co-occurrence_author keywords [38]

In Figure 7, The VOSviewer diagram reveals nanocellulose as the central node around which several thematic clusters radiate: the red cluster focuses on fundamental material properties, cellulose nanofibers, crystallinity, and thermal stability, highlighting core characterization studies; the blue cluster emphasizes biomedical and environmental applications, with terms like “hydrogel,” “antibacterial,” and “water treatment” indicating growing interest in using nanocellulose for drug delivery and filtration; the green cluster centers on composite development, featuring “reinforcement,” “mechanical properties,” and “supercapacitors,” which

underscores efforts to enhance polymer matrices and energy storage devices; and the yellow cluster around “surface modification,” “adsorbent,” and “humidity sensor” points to functionalization strategies for sensors and adsorption technologies. The proximity and interlinking of these colored groups illustrate how advances in fundamental understanding propel diverse applications, while the dense network of connections underscores nanocellulose’s role as a versatile platform uniting materials science, biomedicine, and environmental engineering [39].

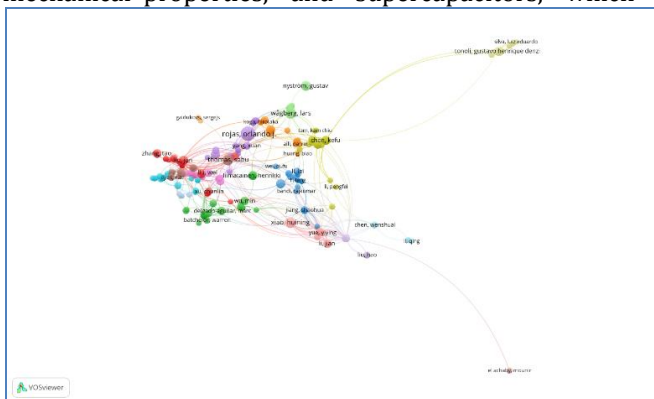


Figure 8. Citation_authors [40]

In Figure 8, The VOSviewer map reveals a tightly interwoven network of researchers clustered around several core author hubs: the red cluster, anchored by “Zhang, Tao” and “Rojas, Orlando J.”, indicates a prolific group focused on nanocellulose modification and composite development, while the green cluster around “Xiao, Huining” and “Batchuluun, Warren” highlights a parallel stream investigating sustainable material sourcing and pulp-to-paper technologies. The blue cluster centered on “Thomas, Sabu” and “Kumar, Bandi” underscores collaborative efforts in biomedical applications and hydrogel formation, and the orange cluster led by “Wågberg, Lars” and “Gällstedt, Mikael” points to fundamental studies in cellulose fiber self-assembly and interface engineering. Peripheral yellow nodes, such as “Silva, Luiz Eduardo” and “Tonoli, Gustavo Henrique Denzi”, suggest emerging contributors in biofilm and packaging research, while

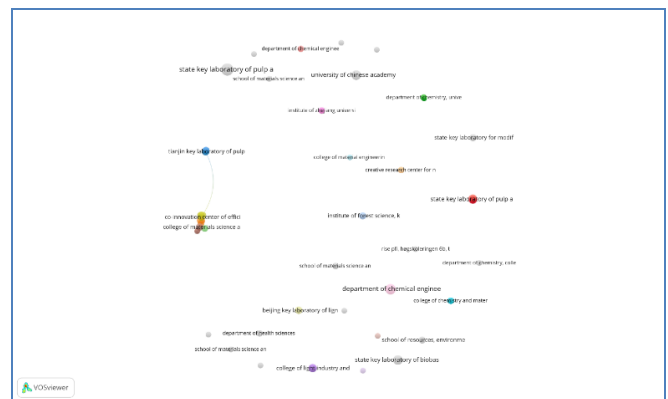


Figure 9. Citation_otganizations [41]

isolated gray nodes like “El Achaby, Mounir” indicate niche specialties with fewer co-authorship ties. The varying node sizes reflect each author’s citation impact, and the density of interconnecting lines illustrates how these thematic communities frequently crosspollinate, driving advances across cellulose science and engineering [42]. In Figure 9, The VOSviewer map depicts institutional collaborations in pulp and materials science, with several thematic clusters emerging. A prominent red cluster centers on the “state key laboratory of pulp and paper,” indicating a major hub where intensive research and co-authorship occur. Nearby, the blue cluster around the “Tianjin key laboratory of pulp” and the “co-innovation center of efficient utilization of forest resources” suggests a regional subnetwork focused on pulp processing and sustainable resource use. The green cluster, anchored by the “department of chemistry, university of Chinese

Academy of Sciences”, highlights interdisciplinary ties linking chemical analysis and modification methods to pulp science. Smaller purple and yellow clusters, such as the “Beijing key laboratory of lignin and cellulose” and the “state key laboratory of biobased materials,” point to niche specializations in lignin valorization and biopolymer development. Scattered gray nodes (various “departments of chemical engineering” and “schools of materials science”) illustrate peripheral or emerging contributors whose weaker link strengths suggest less frequent collaboration with the central hubs. Overall, the spatial arrangement and link thickness reveal how core laboratories drive the field while a diverse set of specialized centers contributes complementary expertise [43].

In Figure 10, The VOSviewer visualization highlights China as the dominant node, by far the largest and most central, indicating its leading role in international research collaborations, particularly with proximate partners such as Hong Kong, Vietnam, the Philippines, Turkey, Serbia, and the Netherlands, all forming a tightly knit cluster. The thick lines radiating from China to these countries reflect high co-authorship frequencies and strong bilateral ties. In contrast, Israel appears as an isolated, much smaller node with no visible links, suggesting limited or emerging collaboration with this primary network. Overall, the

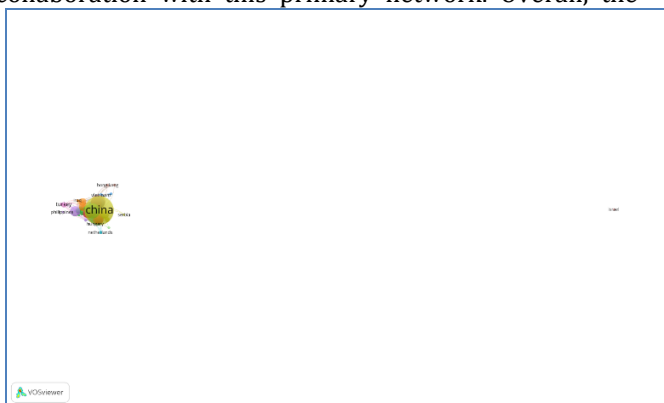


Figure 10. Citation_countries [46]

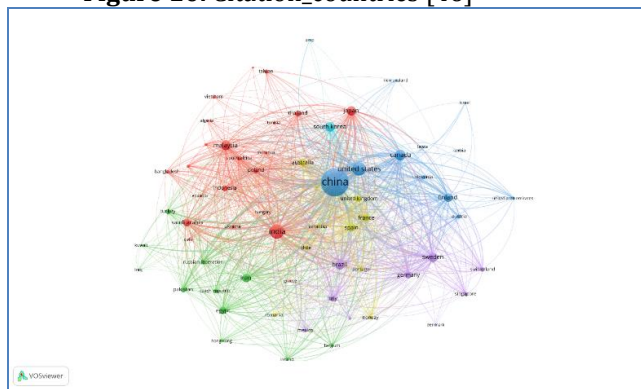


Figure 12. Bibliographic coupling_countries [48]

The blue node in Figure 12 representing China and the large light-blue node symbolizing the United States emerge as key centers of activity, connected by thick lines that reflect strong bilateral co-authorship ties. To the left, a red cluster dominated by India extends to regional collaborators such as South Korea,

map underscores China’s central position in the global research landscape depicted, with a cohesive regional partnership circle and a notable outlier in Israel [44]. In Figure 11, The VOSviewer map reveals a dense central hub (red) dominated by the State Key Laboratory of Pulp & Paper, the Co-innovation Center of Efficient Utilization of Forest Resources, and the University of Chinese Academy of Sciences, indicating they are the primary drivers of collaborative research in pulp and biobased materials. Surrounding this core, a green cluster centers on the State Key Laboratory of Biobased Materials and the Bioresource Technology Division, highlighting a thematic focus on renewable feedstocks and biochemical conversion. A pink cluster, anchored by various Departments of Chemical Engineering, underscores the methodological linkages in catalyst development and process optimization. The blue cluster groups Schools of Chemistry and Environmental Engineering, reflecting interdisciplinary ties in analytical techniques and sustainability assessments. A smaller yellow cluster around Departments of Mechanical Engineering suggests emerging interests in process scale-up and equipment design. Off to the right, the isolated Institute of Forest Science forms a peripheral node, signifying its niche but less integrated role in the broader network [45].

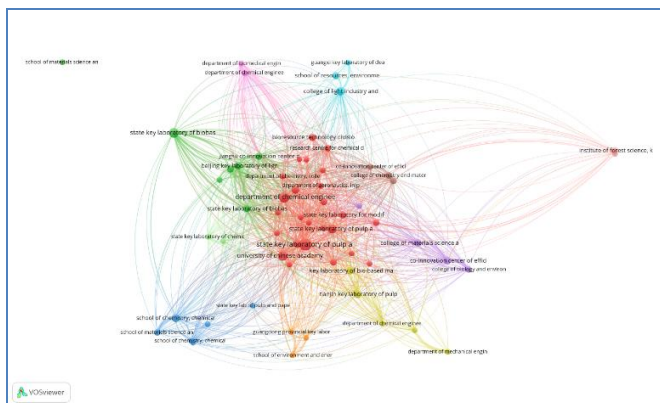


Figure 11. Bibliographic coupling_organizations [47]

Malaysia, Thailand, and Vietnam, illustrating the prominence of Asia-focused research partnerships. Positioned below, a green cluster formed by Iran, Pakistan, and Egypt indicates a distinct collaborative network centered in the Middle East and North Africa. At the center, a yellow cluster consisting of the United Kingdom, France, and Spain functions as a bridge linking the primary hubs to smaller, more peripheral groups. On the right, a purple cluster including Sweden, Germany, Switzerland, and Singapore reveals cooperative links between European and Southeast Asian institutions. The dense arrangement of nodes and the pronounced thickness of connecting lines reflect a high level of global collaboration, indicating that co-authorship networks frequently transcend regional boundaries, creating an interconnected and diverse international research landscape [49].

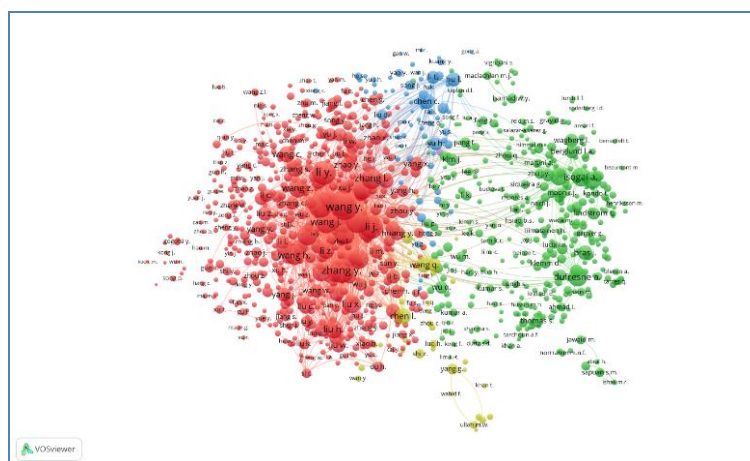


Figure 13. Co-citation_cited authors [50]

In Figure 13, The VOSviewer map reveals a densely interconnected core (red) dominated by authors with the surname Wang and Zhang, indicating a highly collaborative research group with extensive co-authorship ties; adjacent to this core, a green cluster led by figures such as Isogai and Fukuizumi signifies a parallel community focused on fundamental cellulose chemistry and nanofibril isolation. A smaller blue cluster bridging the red and green groups highlights methodological innovators in surface modification and

composite fabrication, while the compact yellow cluster at the bottom, anchored by Uhlmann and Khan, suggests an emerging niche of researchers whose work is just beginning to integrate with the larger network. The relative node sizes reflect each author's citation impact, and the thickness of the connecting lines conveys the frequency of collaboration, together illustrating how a central powerhouse of contributors coalesces with specialized subcommunities to drive advances across cellulose-based materials science [51].



Figure 14. Author Collaboration Network

The results of the study derived from Python-based analysis provided detailed and customizable insights that extended beyond the capabilities of built-in bibliometric tools. By leveraging Python's powerful libraries for data manipulation, statistical analysis, and visualization, such as Pandas, NumPy, Matplotlib, and Seaborn, the study was able to process large volumes of bibliographic metadata with high precision and flexibility. This enabled the generation of dynamic visualizations, including time-series plots of publication

trends, heatmaps of keyword co-occurrence, and geospatial maps of contributing countries. Furthermore, Python scripts allowed advanced filtering, clustering, and correlation analyses, uncovering subtle patterns and relationships within the dataset that were not readily visible through standard visualization platforms. These results significantly contributed to a more nuanced and comprehensive understanding of research developments in the field of cellulose-based nanomaterials [52]. The Author Collaboration Network

Figure 14 displays several clusters of researchers and their co-authorship connections. A central cluster includes authors such as de Oliveira K.M.G., de Sousa Carvalho E.H., and Magalhães W.L.E., indicating a high degree of collaboration among them. Peripheral groups consist of Brenes R.G.R. with Grieco M.A.B., Ornaghi F.G. with Neves R.M. and Zattera A.J., and Hadsell A. with Chau H. and Barber R., each showing a separate collaborative unit. Overall, the network illustrates the different levels and patterns of collaboration among the listed authors [53]. The word cloud, titled "Word Cloud of Article Titles," Figure 15 visualizes the frequency of terms appearing in article titles. The size of each word corresponds to its frequency, with larger words indicating more frequent appearance. Prominent terms

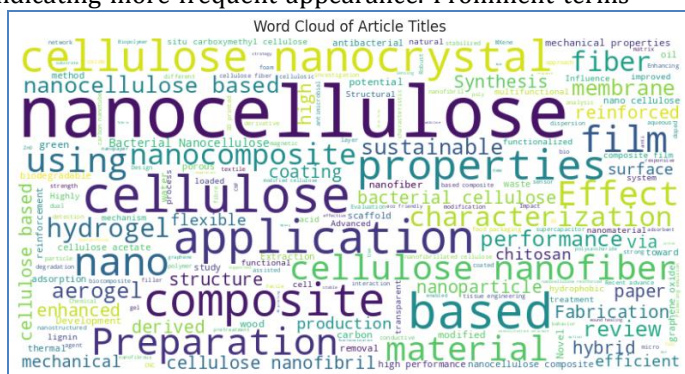


Figure 15. Word cloud of article titles

The infographic in Figure 17 illustrates the number of publications per year from 2021 to 2025. It shows a steady increase from 2021, peaking in 2022 and 2024 with over 750 publications each year. The number slightly declined in 2023 but remained high. However, a significant drop is observed in 2025, with the number of publications falling to around 300. This trend suggests a strong publication output in the early years, followed by a sharp decrease in the most recent year, which may indicate either a delay in reporting, a shift in research priorities, or other external factors affecting publication rates [55]. The bar chart, titled "Top 10 Journals by Number of Publications," Figure 16 compares the number of publications across different journals. "Carbohydrate Polymers" leads with the highest number of publications, exceeding 350. "Cellulose" follows with over 300 publications, and "Polymers" is third with just over 200. "ACS Applied Materials and Interfaces" and "Biomacromolecules" have significantly fewer publications, each with around 50-60. The remaining journals, including "Materials Today: Proceedings," "Advanced Functional Materials," "Journal of Polymers and the Environment," "Journal of Applied Polymer Science," and "Journal of Natural Fibers," each have fewer than 50 publications. Overall, the chart highlights "Carbohydrate Polymers" and "Cellulose" as the leading journals in terms of publication volume, followed by "Polymers", while the remaining journals have considerably fewer

include "cellulose," "nanocellulose," "properties," "application," "composite," "based," "fiber," "film," "characterization," and "preparation," highlighting core research areas. Other notable words such as "hydrogel," "nanocrystal," "nanofiber," "surface," "performance," "material," and "effect" suggest specific characteristics, forms, or outcomes related to cellulose-based research. The presence of terms like "antibacterial," "sustainable," and "mechanical" indicates the exploration of specific properties and applications. Overall, the word cloud provides a snapshot of the key themes and focus areas within the body of articles related to cellulose and nanocellulose [54].

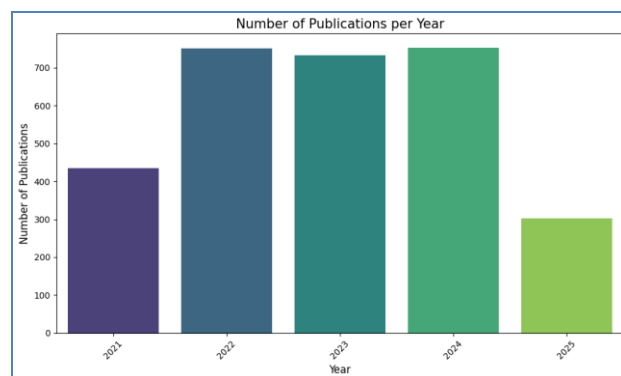


Figure 16. Number of publications per year publications [56].

The "Writers Collaboration Network" Figure 18 depicts a complex web of connections among numerous authors. Each node, labeled with a writer's name (e.g., Zhou Y, Wang B, Li C, Chen X), represents an individual, and the lines connecting them signify collaborative relationships. A densely interconnected central cluster indicates a high degree of co-authorship and collaboration among these writers. Rojas OJ appears as a peripheral node with connections to a subset of the central cluster, suggesting a different or perhaps less frequent collaborative pattern compared to the core group. Overall, the network illustrates the extent and structure of collaborative relationships within this group of writers [57]. The article similarity heatmap (TF-IDF) Figure 19 illustrates the similarity between different articles using a term frequency-inverse document frequency approach. The diagonal red squares indicate that each article is perfectly similar to itself, represented by a similarity score of 1.0. The off-diagonal elements vary in color from blue to red, representing the similarity scores between different articles, with blue indicating low similarity and red indicating high similarity. Most off-diagonal elements are blue, suggesting that the articles have relatively low similarity to each other. Overall, the heatmap shows that while each article is uniquely similar to itself, there is generally low similarity between different articles in the dataset [12].

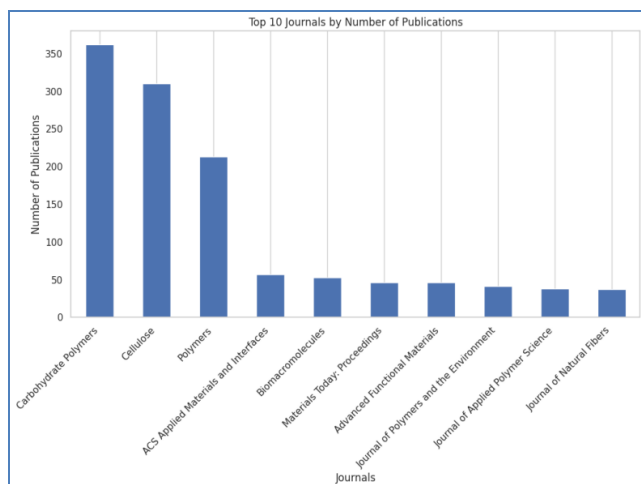


Figure 17. Top 10 journals by number of publications

The bar chart, titled "Research Funding Trends: Top Sponsors by Year," Figure 20 illustrates the number of documents funded by various sponsors from 2021 to 2025. The National Natural Science Foundation of China (NSFC) shows a dominant and increasing trend in funding from 2021 to 2024, followed by a decrease in 2025. The National Key Research and Development Program of China (NKRDPC) maintains a relatively stable but smaller funding level over the years. The Fundamental Research Funds for the Central Universities shows a consistent funding level, while the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the National Research Foundation of Korea (NRF) have the lowest funding levels. Overall, the chart emphasizes the significant increase in research funding by the NSFC until 2024, with a slight decline in 2025, while other sponsors maintain

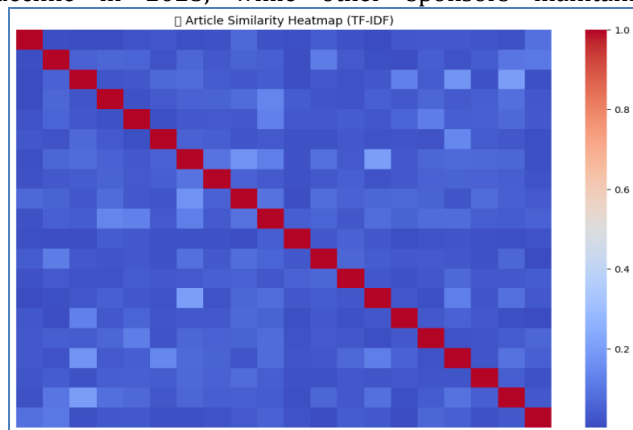


Figure 19. Article similarity heatmap

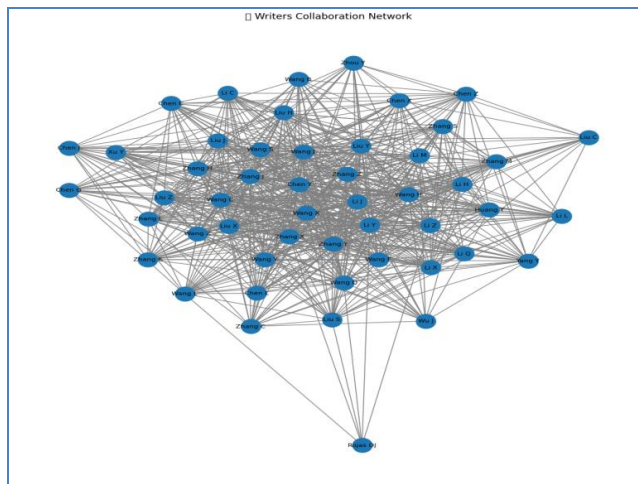


Figure 18. Writers collaborations network

comparatively lower and more stable funding levels [58]. To complement and support the information generated through VOSviewer and Python, we also utilized generative AI (Gen-AI) capabilities, specifically through Scopus Copilot. The process involved creating a structured plan to address our query, conducting a natural language search with the question "What is nanocellulose and its applications?", followed by a comprehensive keyword search using a combination of relevant terms related to nanocellulose properties, sustainability, and applications. This multi-step approach enabled us to gather rich, contextual insights and generate a well-informed summary, ensuring the robustness and relevance of the data used in our analysis. The detailed steps of this Gen-AI-assisted process are illustrated in Figure 21 [59].

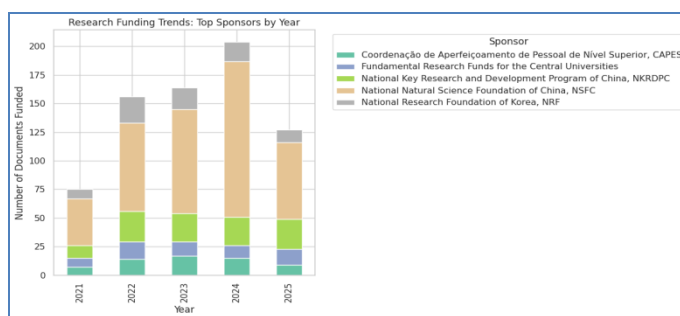


Figure 20. Research funding trends

Nanocellulose possesses exceptional mechanical properties, making it a promising material for various applications. It exhibits high tensile strength, stiffness, and a large specific surface area, rendering it highly suitable for structural and functional uses. Compared to other nanomaterials, nanocellulose demonstrates superior specific stiffness and strength, often surpassing most metals and alloys. Furthermore, nanocellulose offers notable environmental benefits as it is derived from renewable sources like plants and bacteria. It is biodegradable, biocompatible, and non-toxic, contributing positively to sustainability and environmental protection [61]. In terms of production,

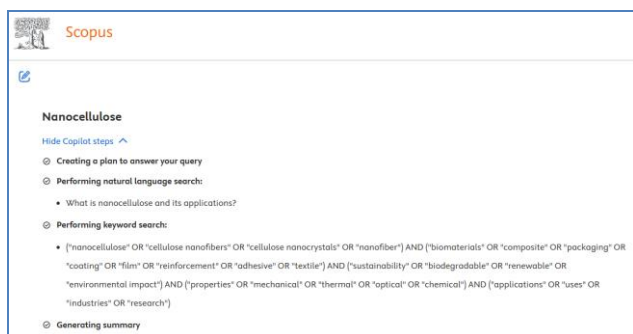


Figure 21. Copilot steps in Scopus-AI [60]

nanocellulose can be extracted through mechanical or chemical processes from sources such as wood, plants, bacteria, and algae. Common methods include acid hydrolysis, mechanical treatment, oxidation, and enzymatic degradation. Modifications using small molecules, macromolecules, and inorganic nanoparticles are applied to enhance their properties for wider applications. In the biomedical field, nanocellulose is increasingly utilized for wound healing, drug delivery, medical implants, and tissue engineering. Its biocompatibility, low cytotoxicity, and high-water retention capacity make it ideal for cell immobilization and targeted drug delivery. Moreover, nanocellulose-based wound dressings have shown effectiveness in accelerating healing by promoting cell proliferation and migration. Overall, nanocellulose stands out as a sustainable and versatile material with broad industrial and biomedical potential [62].

CONCLUSION

This bibliometric and text mining study offers a comprehensive overview of the global research landscape on nanocellulose from 2021 to 2025. China emerges as the most dominant contributor in terms of publication volume, institutional affiliations, and research funding—particularly through agencies like the National Natural Science Foundation of China. Thematic analysis reveals several key application areas, including composite materials, biomedical engineering, environmental remediation, and energy storage. Keyword co-occurrence and topic modeling highlight sustained interest in properties such as crystallinity, mechanical performance, surface modification, and sustainability. However, a notable decline in publication volume in 2025 indicates potential shifts in research focus or funding priorities, suggesting the need for further investigation. The findings underscore the strategic value of bibliometric mapping to inform funding policies, research collaboration strategies, and institutional planning. For researchers, the study provides a clear snapshot of emerging trends and high-impact contributors, facilitating informed topic selection and partnership development. Nonetheless, the study is limited by its exclusive reliance on the Scopus database, which may omit significant contributions indexed elsewhere, such as in Web of Science or PubMed. Future research could expand the scope by integrating multiple databases, conducting field-specific citation analysis, and applying advanced machine learning for deeper thematic discovery. These enhancements would offer a more nuanced understanding of nanocellulose's evolving research frontiers and practical applications.

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