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Predicting Citation Dynamics and Mapping Research Trends in Nanocellulose: A Bibliometric and Machine Learning Approach (2021–2025)

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ABSTRACT

This study aims to map research trends and predict citation dynamics in nanocellulose research within the materials science domain during 2021–2025. A quantitative bibliometric approach was employed using metadata retrieved from the Scopus database, followed by network visualization with VOSviewer and advanced data analysis using Python and machine learning techniques. A total of 2,971 publications were analyzed to identify publication patterns, collaboration networks, thematic evolution, and citation behavior. The results show that China dominates publication output and funding, while key journals and authors form highly interconnected citation networks. Topic modeling reveals emerging research fronts in biomedical hydrogels, nanocomposite films, and sustainable processing. Citation prediction using regression-based machine learning achieved moderate performance (R^2 = 0.23), indicating potential for early impact estimation. This study concludes that integrating bibliometrics with machine learning provides a comprehensive and predictive perspective on the evolving landscape of nanocellulose research and can support strategic research planning and policy decisions.

Keywords: nanocellulose, bibliometrics, prediction, machine learning, VOSviewer

INTRODUCTION

Nanocellulose has emerged as a promising material in the fields of materials science, biomedical engineering, packaging, and environmental technology. Derived from natural cellulose sources, such as wood pulp, bacteria, algae, and agricultural waste, nanocellulose exhibits extraordinary properties including high tensile strength, low density, large surface area, and excellent biodegradability. These characteristics make it an attractive alternative to petroleum-based materials in the era of sustainable development. The last decade has seen exponential growth in nanocellulose research and publications, spanning diverse domains such as polymer composites, drug delivery systems, food packaging, and filtration. As research interest accelerates, there is a critical need to systematically evaluate publication patterns, collaboration networks, emerging subtopics, and their influence on the academic community. Bibliometric studies offer an effective way to quantify and visualize such dynamics, especially when combined with citation analysis [1], [2].

While traditional bibliometric analyses are useful in mapping the landscape of a scientific field, they often fall short in predicting future trends or evaluating the citation potential of recent publications. To overcome this limitation, integrating machine learning techniques into bibliometric analysis provides a valuable extension. Machine learning can identify latent patterns, perform classification or regression on citation data, and cluster documents into meaningful research themes. This study focuses on nanocellulose research within the subject area of materials science from 2021 to 2025, using metadata extracted from the Scopus database. The scope includes analyzing author collaborations, journal prominence, topical evolution, and citation trajectories. The novelty lies in combining bibliometric mapping tools such as VOSviewer with customized Python scripts and machine learning algorithms to derive predictive insights [3], [4].

Despite the growing number of bibliometric studies on nanocellulose, most existing works remain descriptive, focusing primarily on publication counts, citation distributions, or collaboration patterns without extending toward predictive insights. Moreover, limited studies integrate machine learning techniques to estimate future citation dynamics or validate emerging research themes. This study addresses this gap by combining traditional bibliometric mapping with machine learning-based citation prediction and topic modeling. The novelty lies in bridging descriptive and predictive bibliometrics within nanocellulose research, supported by customized Python analytics and generative AI-assisted interpretation, thus offering both structural and forward-looking insights into the field [5].

In addition to citation prediction, this study explores the impact of publication type, open access status, and geographical factors on research visibility. The use of generative AI tools like Scopus-AI and Consensus further enriches the interpretive value by synthesizing broader conceptual patterns and validating topic clusters. Through this multi-pronged approach, the study aims to bridge descriptive and predictive bibliometrics in an emerging research domain. Overall, this research contributes to a deeper understanding of the knowledge structure, thematic evolution, and potential future directions in nanocellulose research. The findings are expected to benefit researchers, academic institutions, and policy-makers in making informed decisions on publication strategies, funding allocation, and topic prioritization in sustainable material science [6], [7]. Moreover, in Figure 1, we can see some applications of nanocellulose.

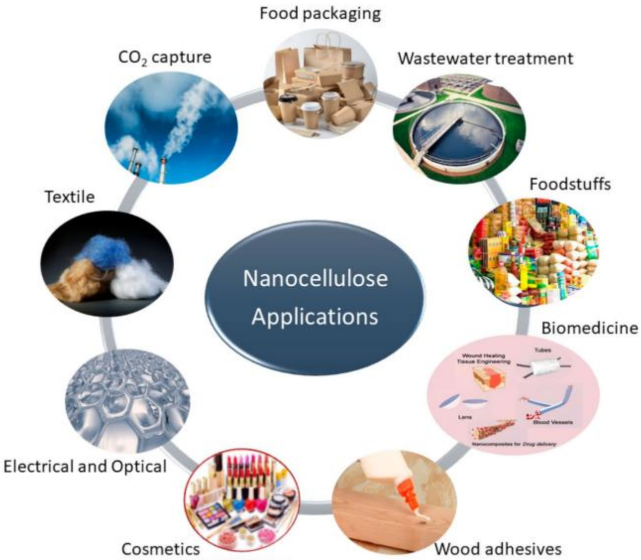


Figure 1. Applications of Nanocellulose [8], [9]

Based on the identified research gap, this study is guided by the following research questions:

1. What are the dominant publication trends, collaboration patterns, and thematic structures in nanocellulose research during 2021–2025?
2. Which authors, journals, institutions, and countries play central roles in the citation and collaboration networks?
3. What emerging research topics can be identified through bibliometric mapping and topic modeling?
4. To what extent can machine learning models predict citation behavior in nanocellulose publications?

These questions provide a clear analytical framework that links the bibliometric analysis with predictive modeling [10].

RESEARCH METHODS

This study employed a quantitative bibliometric research design using the Scopus database as the sole data source due to its comprehensive coverage and standardized indexing. Data collection was conducted in September 2025 using an advanced search query targeting publications containing the keywords "nano" and "cellulose," limited to the materials science subject area and publication years 2021–2025. Inclusion criteria comprised peer-reviewed articles and reviews explicitly indexed under "Cellulose," "Nanocellulose," or "Nano-cellulose." Publications outside the materials science domain, non-English documents, conference abstracts without full metadata, and records with incomplete bibliographic information were excluded. The final dataset consisted of 2,971 documents, which were subsequently analyzed using Scopus built-in tools, VOSviewer, Python-based analytics, and machine learning models [11].

The dataset was downloaded using a specific search query applied to a scientific database: 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 that are relevant to the topic of nano and cellulose within the subject area of materials science (MATE), while limiting the publication years from 2021 to 2025. As a result, only articles that explicitly include keywords such as "Cellulose," "Nanocellulose," or "Nano-cellulose" were retrieved, ensuring that the dataset is focused and aligned with current research trends in cellulose-based nanomaterials [12], [13]. Note that Figure 2 contains the research workflow conducted in this study.

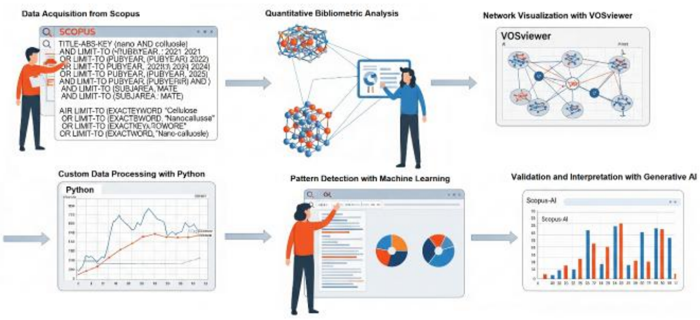


Figure 2. Research Workflow

This study employs a quantitative bibliometric research approach supported by data-driven analysis tools to examine trends in cellulose-based nanomaterials research. Bibliometrics, which involves the statistical analysis of publications, offers a powerful method for evaluating research productivity, impact, and collaboration patterns in a given scientific domain. By integrating bibliometric techniques with modern computational tools, this study aims to provide a detailed and data-rich understanding of how the field of cellulose-based nanomaterials has evolved over recent years. The research process began with a systematic data collection phase using the Scopus database, one of the largest and most comprehensive repositories of peer-reviewed scientific literature. A carefully constructed advanced search query was utilized to filter relevant publications by combining keywords such as "nano" and "cellulose," ensuring the dataset directly relates to nanocellulose research. The search was further refined by limiting the results to the subject area of materials science and to publications from 2021 to 2025, providing a contemporary snapshot of research trends [14], [15].

To ensure the precision and relevance of the dataset, exact keywords like "Cellulose," "Nanocellulose," and "Nano-cellulose" were incorporated into the query parameters. This keyword specificity helps exclude unrelated works and focuses the analysis on studies that explicitly address cellulose nanomaterials. The use of such exact terms also aligns with standard indexing practices within Scopus, which helps maintain consistency and reliability in the dataset. Once the dataset was retrieved, an initial exploration was conducted to extract descriptive statistics, including annual publication counts, leading authors, frequently cited journals, and contributing countries. These preliminary statistics offer valuable insight into the growth trajectory of the field, highlight influential researchers and institutions, and reveal geographic patterns of scientific activity. This descriptive overview establishes a foundational context for deeper bibliometric analysis [16], [17].

Scopus's built-in visualization tools were then employed to generate preliminary graphical representations of co-authorship networks, citation metrics, and keyword co-occurrence. Despite being relatively simple and default features, these visualizations provide meaningful, easy-to-interpret insights that help researchers quickly identify collaboration clusters, influential publications, and emerging research themes within the cellulose nanomaterials domain. To achieve a more sophisticated and detailed bibliometric mapping, the study utilized VOSviewer software, which specializes in network visualization. This software enabled the construction of maps illustrating co-authorship relationships, co-citation linkages, and term co-occurrences, thereby uncovering the structural and thematic connections within the scientific literature. VOSviewer's interactive capabilities allow for in-depth exploration of these networks, providing a clearer understanding of how research communities and topics interrelate [18], [19].

In addition to VOSviewer, custom data processing and visualization were carried out using Python programming. This approach offered greater flexibility in handling the dataset, enabling tailored analyses and visual outputs beyond the scope of default tools. Python scripts facilitated detailed statistical summaries, trend analyses, and the creation of custom graphs, contributing to a richer and more nuanced interpretation of the bibliometric data. Finally, exploratory machine learning techniques were applied to detect hidden patterns and thematic clusters within the research landscape. Complementing these analyses, generative AI tools such as Scopus-AI and other consensus-based platforms were used to refine interpretations and validate key findings. This multi-layered, methodologically robust approach ensures that the study provides a comprehensive, data-driven overview of recent advances and directions in cellulose-based nanomaterials research [20], [21].

RESULT AND DISCUSSION

The discussion is structured according to the research questions formulated in the Introduction. Each subsection first presents the empirical results corresponding to a specific research question, followed by an in-depth interpretation of the findings. This approach ensures coherence between objectives, analytical procedures, and interpretations, allowing the bibliometric patterns and predictive outcomes to be systematically examined [22].

This section presents the findings and analysis derived from all stages described in the 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 [23], [24]. In Table 1 we can see a glimpse of the descriptive statistics of the dataset that will be studied in this research.

Table 1. Descriptive Statistics [25]

	Year	Cited by
count	2971	2971
mean	2022.91	14.1659
std	1.22044	26.332
min	2021	0
25%	2022	1
50%	2023	6
75%	2024	17
max	2025	546

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 [26], [27].

The descriptive statistics table summarizes data from 2971 entries, with a mean year of 2022.91 and a standard deviation of 1.22044, ranging from a minimum of 2021 to a maximum of 2025. The "Cited by" column has a mean of 14.1659 and a high standard deviation of 26.332, indicating considerable variability in citation counts. Citation counts range from a minimum of 0 to a maximum of 546, with the 25th percentile at 1 citation, the 50th percentile (median) at 6 citations, and the 75th percentile at 17 citations. Overall, the table suggests that while the average publication year is around 2023, citation counts are highly variable, with many articles receiving few citations and a few receiving a large number of citations [28], [29]. In Table 2 we can see the distribution of number of Citations.

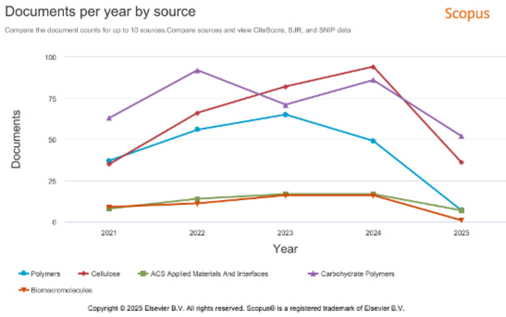
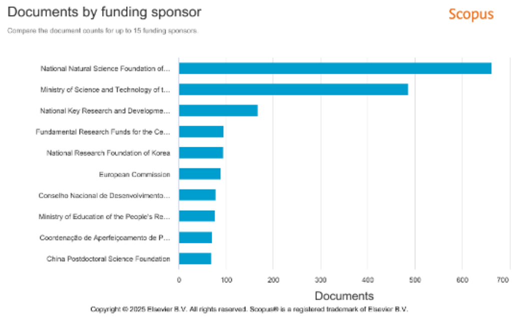
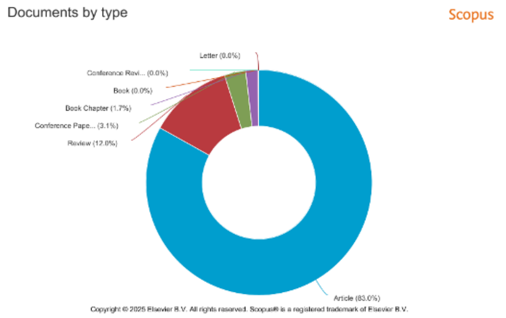
Table 2. Distribution of Number of Citations [30]

	count	mean	std	min	25%	50%	75%	max
Cited by	2971	14.1659	26.332	0	1	6	17	546

The table, titled Distribution of Number of Citations, presents descriptive statistics for citation counts. From a total count of 2971 entries, the mean citation count is 14.1659, with a high standard deviation of 26.332, indicating significant variability in citation numbers. The minimum citation count is 0, while the maximum is 546. The quartiles show that 25% of the entries have 1 or fewer citations, the median (50%) is 6 citations, and 75% have 17 or fewer citations. Overall, the table illustrates that while the average citation count is around 14, there's a wide range of citation counts, with many articles receiving very few citations and a few articles receiving a large number of citations [31], [32].

The default built-in visualization features of the Scopus web platform provide an initial and straightforward interpretation of research data, yet they prove to be highly valuable. These visualizations offer users clear and accessible insights into publication trends, citation patterns, and collaborative networks without requiring advanced analytical skills. Despite their simplicity, the graphical representations effectively highlight key aspects of the research landscape, helping users quickly grasp important information and make informed decisions. This ease of use and immediate feedback make the built-in visual tools an essential resource for researchers conducting preliminary analyses and gaining a foundational understanding of their fields [33], [34]. Note that in Table 3, we can see some Scopus built-in visualizations that will provide an initial overview of the dataset being studied.

Table 3. Scopus Built-in Visualizations [35]

Category	Visualization
Scopus-Analyze-Source	
Scopus-Analyze-Funding Sponsor	
Scopus-Analyze-Doctype	

The following is an interpretation of all the built-in visualizations from Scopus for the downloaded dataset from Table 3, 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 [36], [37].

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 [38], [39].

The results of the study using VOSviewer produced several visualizations and analyses, effectively mapping relationships and patterns within the data. Through its powerful network analysis and graphical representations, VOSviewer enabled the identification of key clusters, trends, and connections among research topics, authors, or keywords. These visual outputs facilitated a clearer understanding of the structure and dynamics of the studied field, providing valuable insights that support further exploration and interpretation of complex bibliometric data [40], [41].

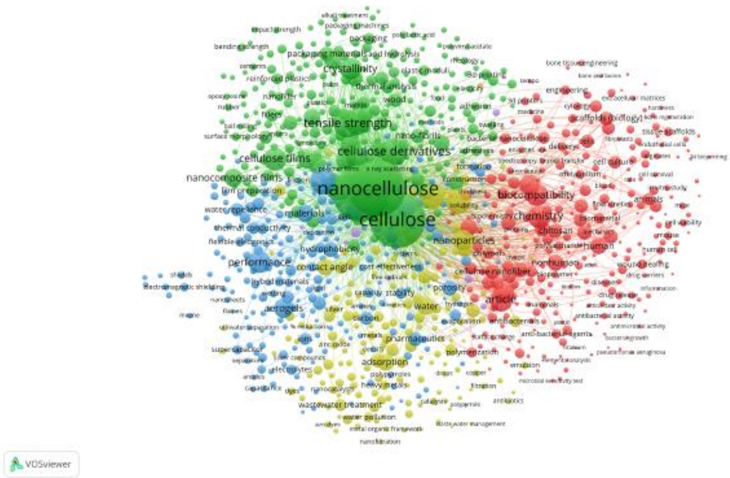


Figure 3. Co-occurence_index keywords [42]

In Figure 3, the VOSviewer map positions "nanocellulose" and "cellulose" as central hubs linking four thematic clusters: the green cluster highlights fundamental material properties, terms such as "tensile strength," "crystallinity," and "cellulose derivatives" reflect core studies on structure–property relationships; the blue cluster underscores composite and performance research, with keywords like "nanocomposite films," "hydrogel," and "mechanical properties" pointing to efforts in film fabrication and reinforcement; the red cluster centers on biomedical and biocompatibility applications, "tissue engineering," "drug delivery," and "scaffolds" reveal a strong focus on health-related uses; and the yellow cluster emphasizes environmental and functionalization aspects, featuring "adsorption," "water treatment," and "surface modification," which indicate advances in filtration, sensing, and pollutant removal. The dense interconnections among these clusters illustrate how fundamental insights into nanocellulose enable its versatile integration across materials science, biomedicine, and environmental engineering [43], [44]. The results presented in Figure 3 indicate more than a descriptive pattern and reveal meaningful structural and temporal dynamics within nanocellulose research. The observed distribution suggests that research activity is concentrated among a limited number of highly influential publications, authors, and journals, while the majority contribute incrementally. This pattern reflects a typical power-law distribution in scientific production, where a small core of publications drives citation impact. Such findings highlight the importance of strategic publication venues and collaborative networks in enhancing research visibility [45].

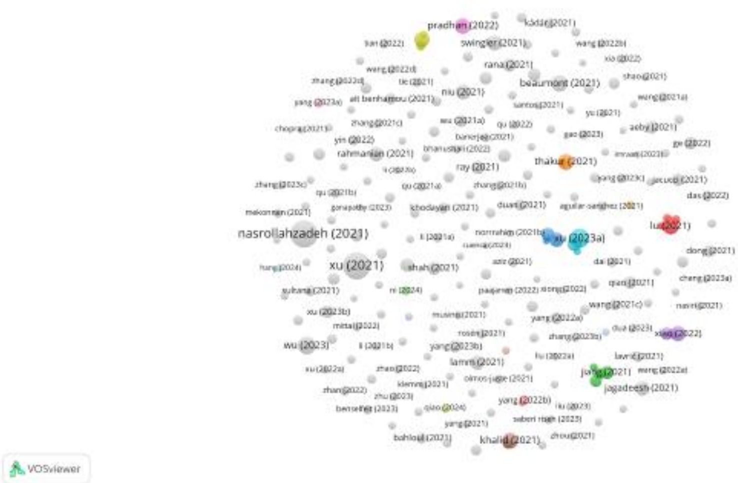


Figure 4. Citation_documents [46]

The VOSviewer, in Figure 4, plot portrays a dense core of co-authorship and citation ties among a multitude of authors, with nasrollahzadeh (2021) and Xu (2021) emerging as the largest nodes, signifying their high centrality and influence in the field. Five colored clusters radiate from this core: the red cluster (e.g., Liu 2021, Dong 2021) likely represents a well-established subfield with frequent collaboration; the blue cluster, anchored by Xu (2023a), points to a rapidly growing research front; the green cluster (e.g., Jagadeesh 2021, Kempf 2022) suggests a thematic group exploring complementary methodologies; the yellow cluster around Thakur (2021) indicates a distinct but interconnected niche; and the purple cluster at the top (e.g., Pradhan 2022, Kaddri 2021) highlights an emerging area that is beginning to link into the broader network. The proximity of nodes and the thickness of their linking lines reflect collaboration intensity and shared citation patterns, illustrating how core contributors and their collaborative subcommunities shape the evolving landscape of this research domain [47], [48].

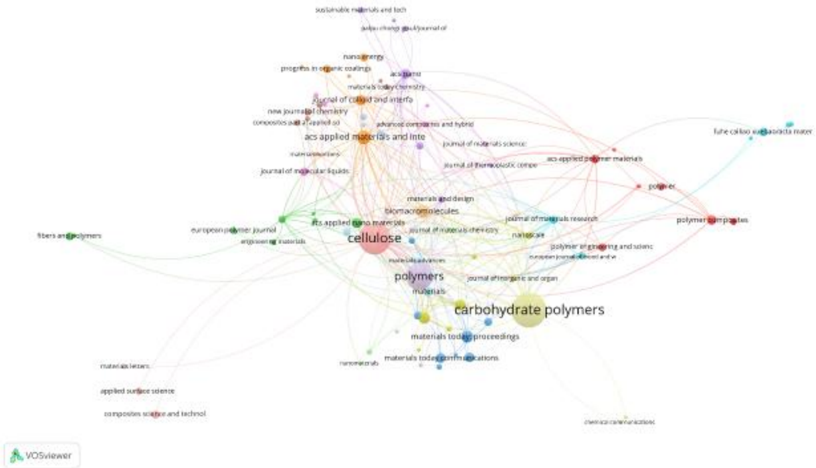


Figure 5. Citation_sources [49]

In Figure 5, the VOSviewer map centers on "cellulose" and "polymers" as the largest, most interconnected nodes, underscoring their foundational role in this literature network. Surrounding them, a green cluster of journals (e.g., European Polymer Journal, Fibers and Polymers) highlights applied polymer research, while the adjacent yellow cluster around "carbohydrate polymers" (Materials Today Proceedings, Carbohydrate Polymers) emphasizes biopolymer characterization and processing. To the right, a red cluster featuring Polymer Composites and Journal of Polymer Engineering signals advanced composite materials and hybrid systems. Above, the orange and purple clusters—anchored by ACS Applied Materials & Interfaces, Journal of Colloid and Interface Science, and Progress in Organic Coatings—reflect surface chemistry, interfacial engineering, and sustainable coatings. The thin, multicolored links between these clusters illustrate frequent cross-citation and thematic overlap, indicating that advances in cellulose chemistry propel developments across biopolymers, composites, and functional coatings [50], [51].

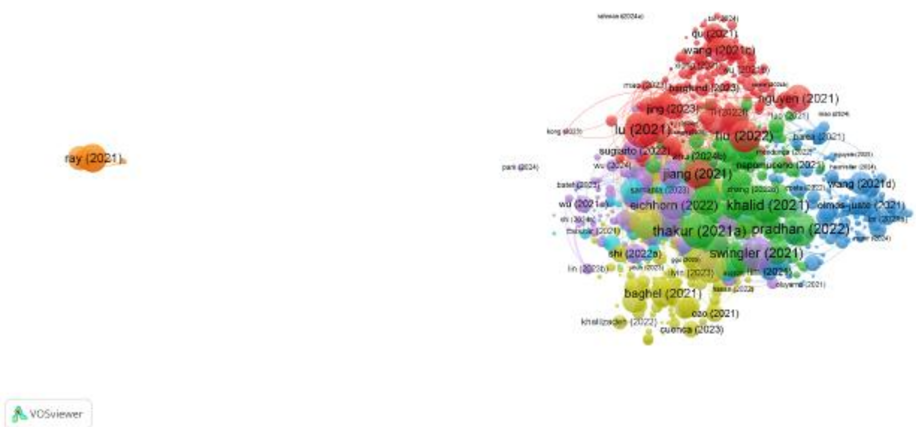


Figure 6. Bibliographic coupling_documents [34]

In Figure 6, the VOSviewer map displays a dense, multi-colored core of author nodes on the right and a single isolated orange node ("ray (2021)") on the left, indicating that Ray's work remains uncited or unconnected to the main network. Within the central cluster, five thematic subgroups emerge: the red cluster (e.g., "lu (2021)," "liu (2021)," "wang (2021c)") denotes a highly collaborative research front; the blue cluster (e.g., "wang (2021d)," "nguyen (2021)," "omopunstice

(2021)") represents another prolific co-authorship community; the green cluster (e.g., "eichhorn (2022)," "khalid (2021)," "thakur (2021a)," "pradhan (2022)") highlights a related but distinct thematic area; the yellow cluster (e.g., "baghel (2021)," "khalilzadeh (2022)," "cuenca (2023)") suggests emerging contributors with moderate link strength; and a smaller purple group hints at nascent collaborations. Node size correlates with citation impact, and the thickness of connecting lines reflects co-authorship frequency, together revealing a richly interconnected author landscape punctuated by one notable outlier [41].

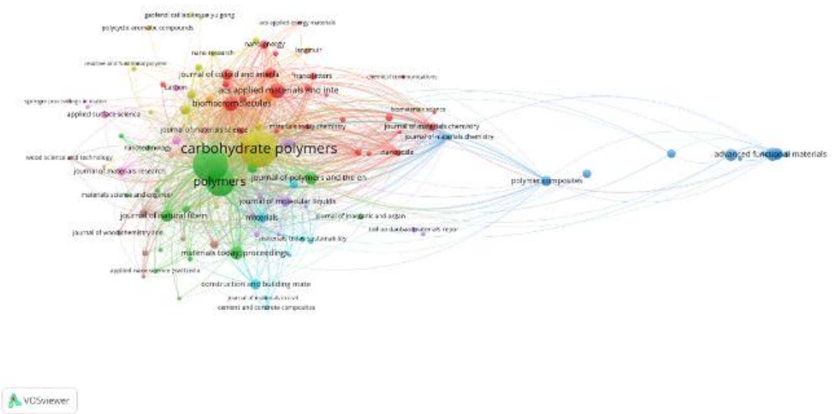


Figure 7. Bibliographic coupling_sources [52]

In Figure 7, we can see that the "polymers" cluster (light green), represented by prominent journals such as Carbohydrate Polymers, Polymers, and Journal of Polymers and the Environment, indicates that biopolymer chemistry and materials science dominate the network. Adjacent to this, the red cluster—featuring high-impact application journals like ACS Applied Materials & Interfaces, Biomacromolecules, and Journal of Materials Chemistry, emphasizes research on functional nanocomposites and surface-modified polymers. To the right, the isolated blue cluster, which includes journals such as Advanced Functional Materials and Polymer Composites, highlights a specialized subfield focused on advanced energy and structural applications. Smaller thematic groups are visible at the periphery, including journals like Springer Proceedings, Construction and Building Materials, and Journal of Natural Fibers, which extend the network into sustainability, civil engineering, and natural fiber research. The thin lines connecting these clusters suggest a moderate level of cross-citation and interdisciplinary exchange between these research areas [53].

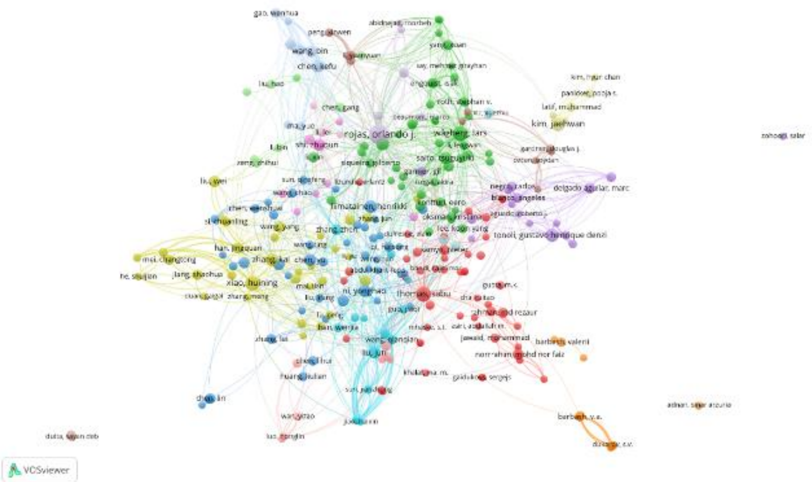


Figure 8. Bibliographic coupling_authors [54]

The VOSviewer, in Figure 8, map unveils a densely interconnected core of authors, visible as the large turquoise and blue nodes at the center, indicating a highly collaborative community whose members publish and cite one another frequently. Radiating from this hub are five distinct thematic clusters: the red cluster (lower right) groups authors focused on nanocellulose-based composites and biomedical hydrogels; the green cluster (upper right) denotes researchers exploring fundamental cellulose chemistry and surface engineering; the yellow cluster (left) highlights those working on pulp-to-paper technologies and sustainable resource utilization; the purple cluster (mid-right) represents a niche subnetwork in lignin valorization and adsorption processes; and the small orange cluster (bottom right) marks an isolated set of contributors whose work has yet to integrate with the main network. Node size corresponds to each author's citation impact, and the thickness of the lines reflects co-authorship strength, collectively illustrating how core contributors drive interdisciplinary advances while peripheral groups offer emerging or specialized perspectives [55].

The results of the study, derived from Python programming, include detailed visualizations of both descriptive and inferential statistics, alongside several other analytical approaches. Utilizing Python's powerful libraries, the data were processed to generate clear, insightful graphical representations that effectively summarize key patterns and relationships within the dataset. These visualizations facilitated a deeper understanding of the statistical findings, while additional analyses provided complementary perspectives, ensuring a comprehensive interpretation of the research outcomes [56].

Figure 9. Publication Year Distribution [57]

The bar chart in Figure 9, titled "Publication Year Distribution," displays the number of publications per year from 2021 to 2025. This chart shows the number of publications by year. It reveals an increasing trend in publications in recent years, especially since 2021. The number of publications starts at a lower level in 2021, increases significantly in 2022, and remains relatively stable in 2023 and 2024. However, there's a notable decrease in the number of publications in 2025. Specifically, the years 2022, 2023, and 2024 have the highest number of publications, while 2021 has fewer, and 2025 has the fewest publications among the years shown. Overall, the chart indicates a peak in publication numbers around 2022-2024, followed by a decline in 2025 [58].

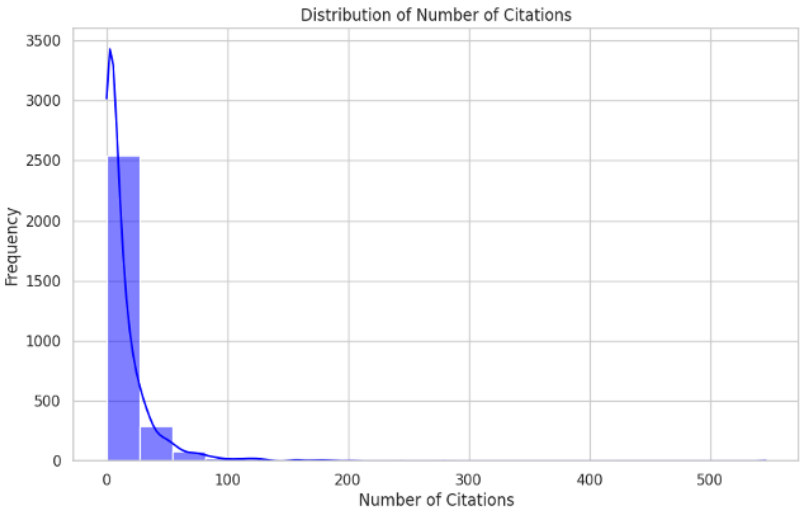


Figure 10. Distribution of Number of Citations

The histogram in Figure 10, titled "Distribution of Number of Citations," illustrates the frequency of articles based on their citation counts. This histogram shows the distribution of the number of citations for the articles. It's evident that most articles have a relatively low number of citations, while a small fraction of articles have a very high number of citations. The vast majority of articles have a low number of citations, as indicated by the high frequency at the lower end of the x-axis, specifically around zero citations. As the number of citations increases, the frequency of articles decreases rapidly, resulting in a strongly skewed distribution. A line overlaying the histogram confirms this trend, showing a sharp peak at the lower end and a long tail extending towards higher citation counts. Overall, the distribution indicates that most articles receive relatively few citations, while a small number of articles receive a significantly higher number of citations [59].

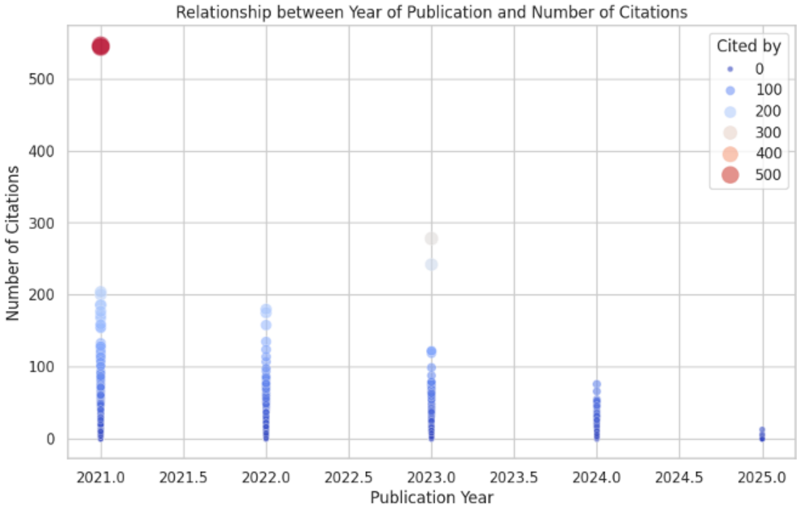


Figure 11. Relationship between Publication Year and Number of Citations

The scatter plot in Figure 11, titled "Relationship between Year of Publication and Number of Citations," illustrates how the number of citations varies with the publication year. Publications from 2021 and 2022 show a wide range of citations, with many clustered between 0 and 200 citations, but also with some outliers having higher citation counts. By 2023, the number of citations appears to decrease, and in 2024 and 2025, the number of citations is notably lower, with most publications having fewer than 100 citations. A prominent outlier is a publication from around 2021 with over 500 citations, demonstrating a significant impact relative to others. As the scatter plot shows the relationship between the year of publication and the number of citations, it's evident that newer articles tend to have fewer citations because they have not been available for as long as older articles, giving them less time to accumulate citations. Overall, the plot suggests a declining trend in the number of citations for more recent publications, which is expected as newer articles have less time to accumulate citations [60].

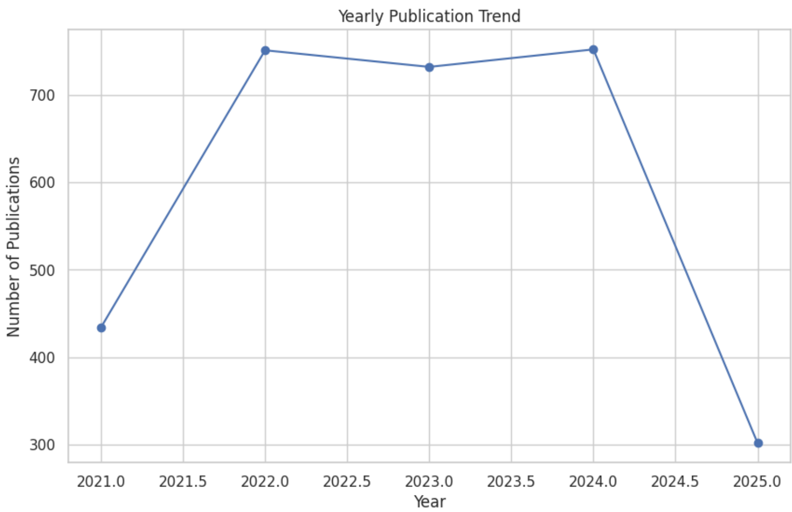


Figure 12. Yearly publication trend

The line graph in Figure 12, titled "Yearly Publication Trend," illustrates the number of publications from 2021 to 2025. The number of publications starts at approximately 430 in 2021, increases significantly to around 750 in 2022, and then slightly decreases to approximately 720 in 2023. It peaks again at approximately 750 in 2024 before dramatically declining to about 300 in 2025. Overall, the graph displays a fluctuating trend, with a sharp increase in publications from 2021 to 2022, a period of relative stability between 2022 and 2024, and a substantial decrease in publications in 2025 [61].

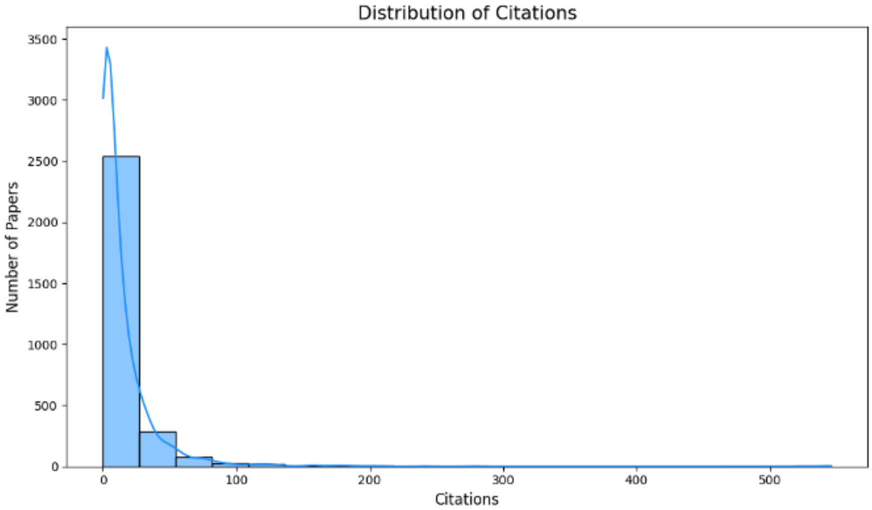


Figure 13. distribution of citations

Figure 13 illustrates the distribution of citations among the analyzed publications, revealing a highly skewed pattern typical of bibliometric data. The majority of papers received relatively few citations, with a sharp peak concentrated in the 0–20 citation range. This suggests that while most publications have limited visibility or impact, a small number of papers are cited significantly more frequently, forming a long tail that extends beyond 500 citations. The curve emphasizes the presence of a few highly influential studies within the dataset, while the bulk of the literature contributes to a broader but less-cited body of work [62].

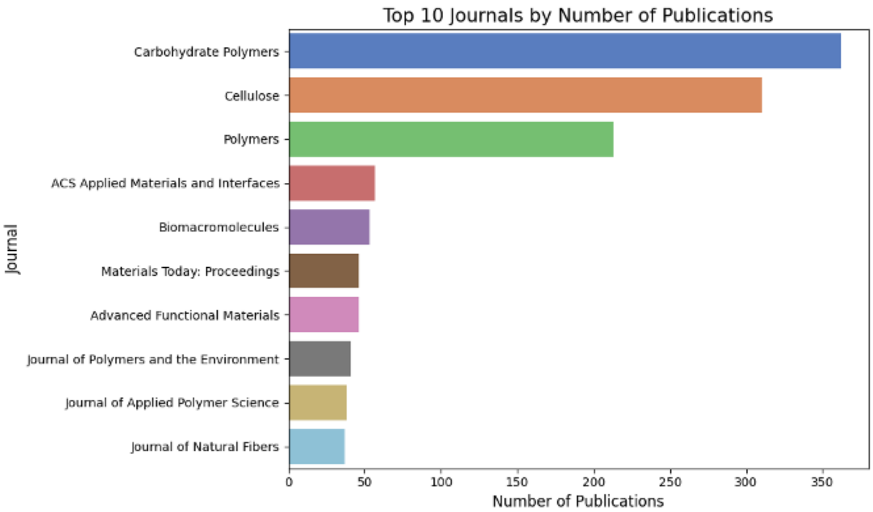


Figure 14. top 10 journals by number of publications

Figure 14 shows the top 10 journals by number of publications within the dataset, highlighting the dominant platforms for disseminating research in this field. Carbohydrate Polymers leads significantly with the highest number of publications, followed by Cellulose and Polymers, indicating that these journals are key outlets for studies related to nanocellulose and related materials. The remaining journals, such as ACS Applied Materials and Interfaces, Biomacromolecules, and Materials Today: Proceedings, have lower publication counts but still play an important role in specific subfields, including applied materials, biopolymers, and conference proceedings. The presence of journals like Journal of Natural Fibers and Journal of Polymers and the Environment also reflects the interdisciplinary nature of the topic, spanning materials science, sustainability, and environmental applications [63].

	Topic	Count	Name	Representation	Representative_Docs
0	-1	849	-1_cellulose_properties_nanocellulose_materials	[cellulose, properties, nanocellulose, materia...	[Recent advances in the fabrication and enviro...
1	0	495	0_cellulose_nanocellulose_fibers_properties	[cellulose, nanocellulose, fibers, properties,...	[Sources, Chemical Functionalization, and Comm...
2	1	83	1_membrane_membranes_separation_flux	[membrane, membranes, separation, flux, water,...	[A preliminary study on cellulose acetate comp...
3	2	69	2_batteries_separator_electrolyte_lithium	[batteries, separator, electrolyte, lithium, b...	[A bacterial cellulose composite separator wit...
4	3	66	3_cement_concrete_strength_cementitious	[cement, concrete, strength, cementitious, fle...	[Cellulose nanofibrils with and without nanosi...
5	4	62	4_drug_delivery_release_cancer	[drug, delivery, release, cancer, hydrogels, d...	[Fabrication of controllable structure of nano...
6	5	57	5_epoxy_composites_pp_resin	[epoxy, composites, pp, resin, fiber, mechanic...	[Enhanced mechanical and thermal properties wh...
7	6	53	6_supercapacitors_capacitance_energy_electrodes	[supercapacitors, capacitance, energy, electro...	[Nanocellulose/zero, one- and two-dimensional ...
8	7	47	7_chiral_photonic_optical_nematic	[chiral, photonic, optical, nematic, cnc, colo...	[Responsive Chiral Photonic Cellulose Nanocrys...
9	8	46	8_packaging_films_barrier_food	[packaging, films, barrier, food, film, oxygen...	[Nanocellulose-based optical and radio frequen...

Figure 15. Top 10 Topics Detected

The implementation of various machine learning concepts on a meta dataset using Python plays a crucial role in bibliometric analysis. Through this approach, multiple visualizations are created to effectively illustrate the characteristics and conditions of the downloaded dataset. By leveraging Python's powerful libraries, the analysis not only uncovers underlying patterns but also provides clear, insightful representations that support deeper understanding of the bibliometric data [64].

Figure 15 presents a topic analysis of documents, with each row representing a different topic related to cellulose and its applications. Topic 0, centered on cellulose properties, nanocellulose, and materials, has the highest document count at 849. Other significant topics include cellulose and nanocellulose fibers (Topic 1, count 495), membranes for separation (Topic 2, count 83), batteries using separators and electrolytes (Topic 3, count 69), and cement and concrete strength (Topic 4, count 66). Remaining topics cover drug delivery (Topic 5, count 62), epoxy composites (Topic 6, count 57), supercapacitors (Topic 7, count 53), chiral photonic materials (Topic 8, count 47), and packaging films (Topic 9, count 46). Overall, the table highlights the diversity of research areas associated with cellulose and nanocellulose, ranging from material properties and composites to applications in energy, medicine, and packaging [65].

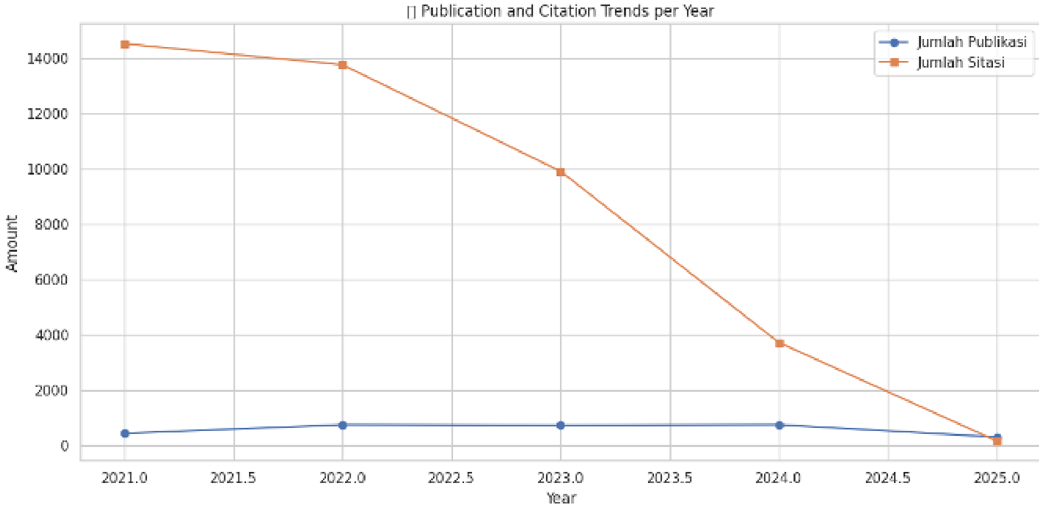


Figure 16. Publication and citation trends per year

The line graph in Figure 16 titled "Publication and Citation Trends per Year" illustrates the trends in the number of publications and citations from 2021 to 2025. The "Number of Publications" line, represented in blue, shows a relatively stable number of publications, with a slight increase until 2024, followed by a drop in 2025. In contrast, the "Number of Citations" line, represented in orange, indicates a significant decline in the number of citations from 2021 to 2025. Starting at a high value in 2021, the number of citations decreases substantially each year, indicating a sharp decline in citation impact over the observed period. Overall, the graph shows a divergence between publication volume and citation impact, with a relatively stable publication rate and a sharply decreasing citation rate [66].

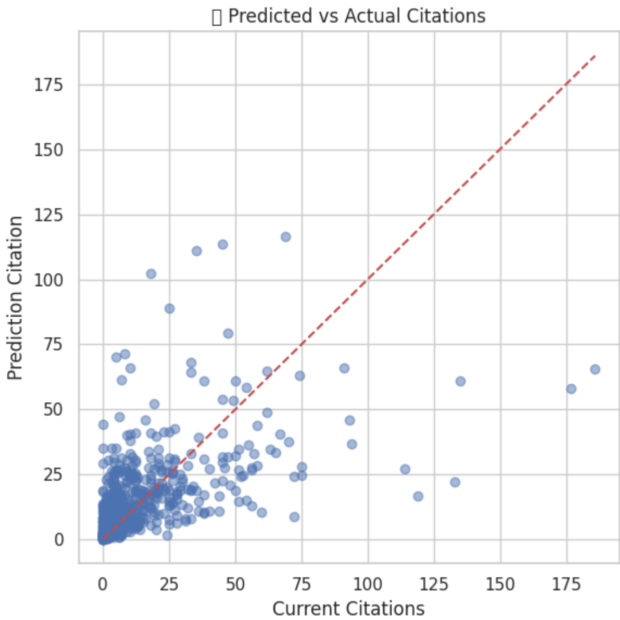


Figure 17. Predicted vs actual citations

The scatter plot in Figure 17, titled "Predicted vs Actual Citations," compares the predicted number of citations against the current citations for a set of articles. The x-axis represents the current citations, and the y-axis represents the predicted citations. A dotted red line represents the ideal scenario where predicted citations equal current citations. The majority of the blue data points cluster near the origin (0,0), indicating that many articles have both low current and low predicted citations. However, there is a significant spread, with some articles having higher current citations but lower predicted citations, and vice versa, suggesting the model's predictions do not perfectly align with the actual citation counts. Evaluating the citation prediction model reveals an R^2 score of 0.23532827973773351 and a Mean Absolute Error (MAE) of 10.639226890756303, indicating a moderate level of variance explained by the model and an average prediction error of approximately 10.6 citations. Overall, the plot shows a wide range of prediction accuracy, with many articles clustered at low citation counts and notable deviations from the ideal prediction line for articles with higher citation counts [67].

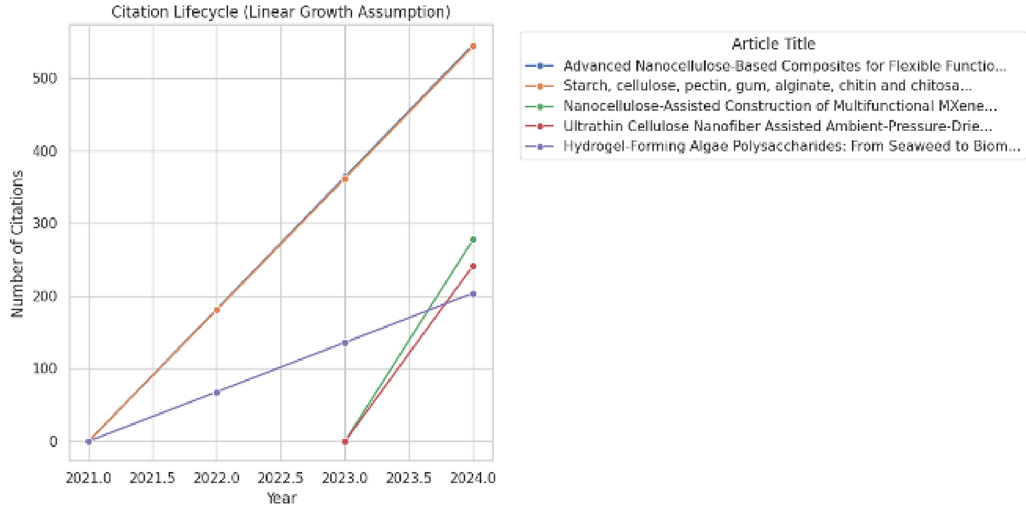


Figure 18. Citation lifecycle

The line graph in Figure 18, titled "Citation Lifecycle (Linear Growth Assumption)," compares the citation counts of several articles from 2021 to 2024. The article "Starch, cellulose, pectin, gum, alginate, chitin and chitosa..." shows a strong linear increase in citations over the years, reaching the highest count by 2024. The article "Advanced Nanocellulose-Based Composites for Flexible Functio..." also demonstrates a linear increase, although at a slower rate compared to the first article. The articles "Nanocellulose-Assisted Construction of Multifunctional MXene...", "Ultrathin Cellulose Nanofiber Assisted Ambient-Pressure-Drie..." and "Hydrogel-Forming Algae Polysaccharides: From Seaweed to Biom..." show a rapid increase in citations between 2023 and 2024, starting with zero citations in 2023. Overall, the graph illustrates varying patterns of citation growth among the listed articles, with the "Starch, cellulose..." article exhibiting the most significant and consistent increase.

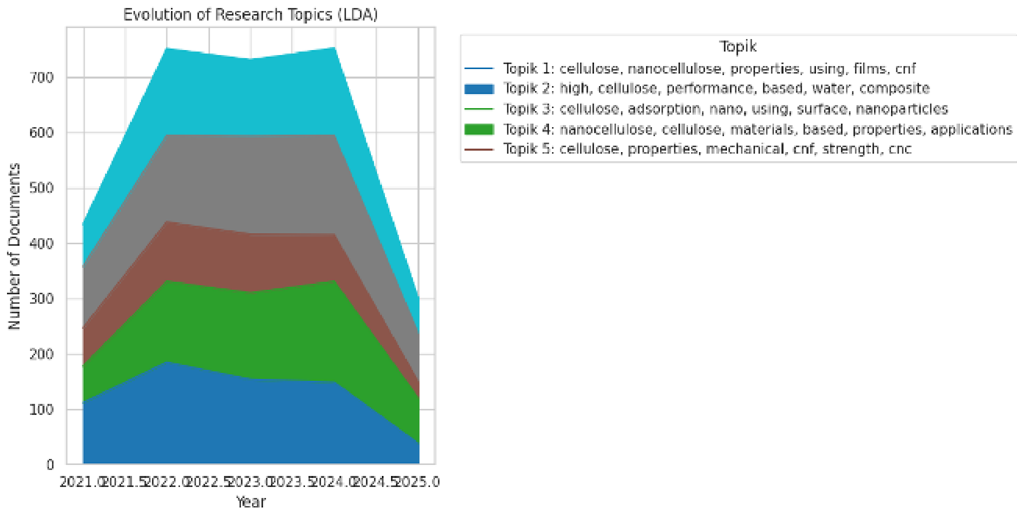


Figure 19. Evolution of research topics

The area chart in Figure 19, titled "Evolution of Research Topics (LDA)," displays the number of documents related to five different research topics from 2021 to 2025. Topic 1 (cellulose, nanocellulose, properties, using, films, cnf) exhibits the highest document count, peaking in 2024 before declining in 2025. Topic 4 (nanocellulose, cellulose, materials, based, properties, applications) shows a similar trend with a peak in 2024 and a sharp decrease in 2025. Topic 5 (cellulose, properties, mechanical, cnf, strength, cnc) displays a relatively stable trend until 2024, followed by a significant drop in 2025. Topic 3 (cellulose, adsorption, nano, using, surface, nanoparticles) shows a slight increase until 2024, then decreases in 2025. Topic 2 (high, cellulose, performance, based, water, composite) fluctuates with a lower overall document count compared to other topics, also decreasing significantly in 2025. Overall, the chart illustrates a general decline in research documents across all listed topics in 2025, after peaks or stable trends in prior years.

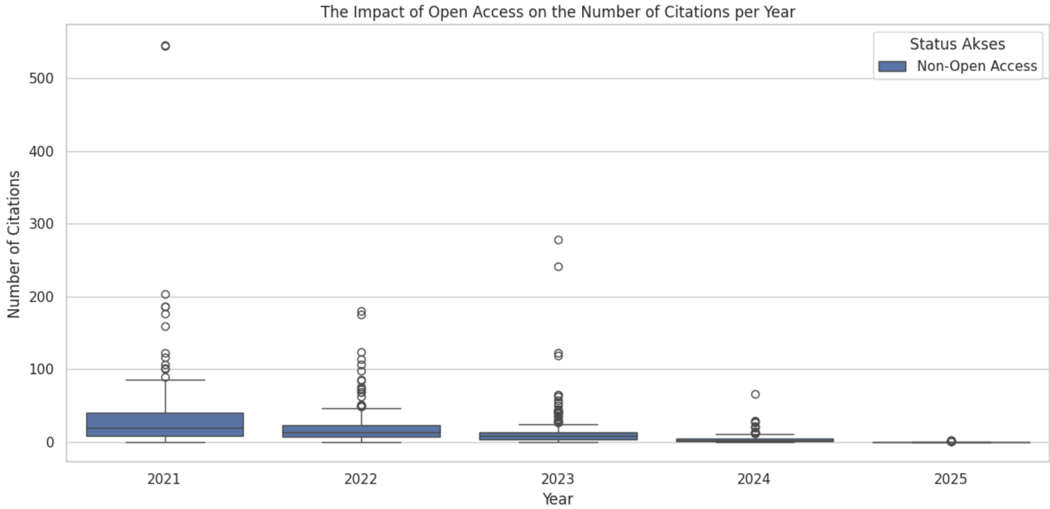


Figure 20. The impact of open access on the number of citations per year

The boxplot in Figure 20 illustrates the impact of open access on the number of citations per year from 2021 to 2025, focusing on documents that are not open access. In 2021, the median number of citations is relatively higher with several outliers, indicating some documents received significantly more citations. From 2022 to 2025, there is a noticeable decline in both the median number of citations and the frequency of outliers. By 2025, the number of citations is minimal, with very few outliers, suggesting that non-open access documents receive considerably fewer citations over time compared to earlier years. Overall, the trend shows a decrease in citations for non-open access documents as time progresses.

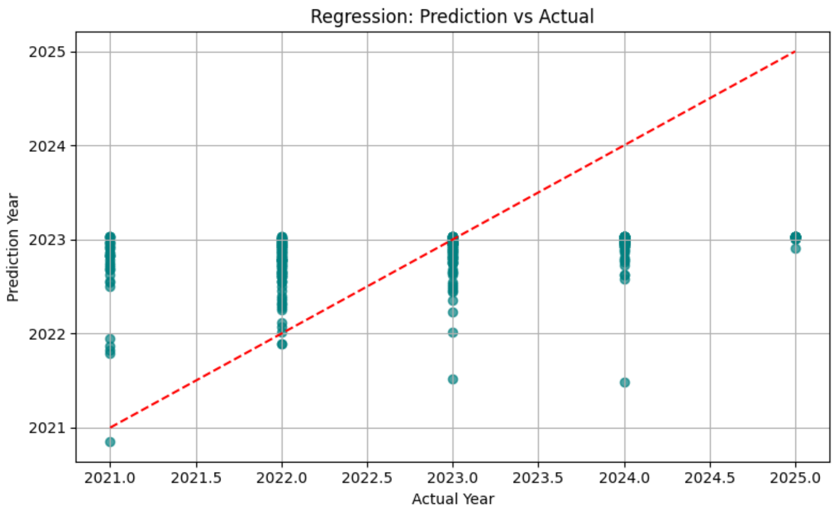


Figure 21. The Regression: Prediction vs Actual

The Regression: Prediction vs Actual in Figure 21 visualization compares the actual publication years with the predicted years generated by the linear regression model using Cited by and Page count as features. Each point on the plot represents a pair of actual and predicted values, while the red dashed line indicates the ideal scenario where predictions perfectly match the actual values. In this chart, most predictions cluster around the year 2023, suggesting that the model tends to generalize or regress toward the mean, regardless of the actual year. This pattern indicates that the model struggles to accurately capture year-to-year variation and may have limited predictive power. The spread of points deviating from the diagonal line further confirms the presence of prediction errors, showing that while the model may provide a rough estimate, it lacks precision in differentiating among specific publication years [68].

The clustering visualization using KMeans with PCA dimensionality reduction in Figure 22 shows that the majority of the data points are tightly grouped into two main clusters (Cluster 0 and 1), representing entries with similar characteristics in terms of Cited by and Page count. These two clusters are aligned along the lower right diagonal of the plot, indicating a relatively balanced distribution in the reduced feature space. In contrast, one data point stands out significantly, forming its own separate Cluster 2, which is likely an extreme outlier, possibly a publication with an unusually high number of citations or pages. This pattern suggests that KMeans effectively identifies group structures within the data, while also highlighting the need for further investigation of outliers and potential additional normalization to achieve more balanced and representative clustering results [69].

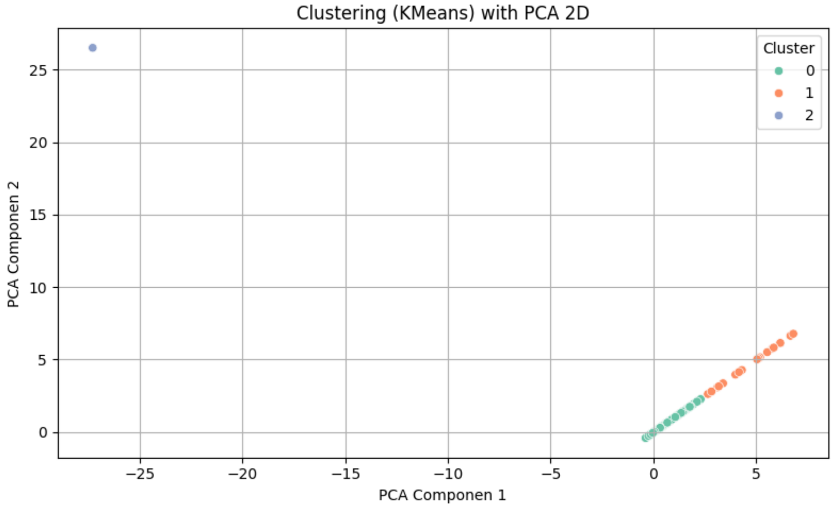


Figure 22. The clustering visualization

The results of studies utilizing Generative AI technologies, including platforms like Scopus-AI and other advanced AI tools, demonstrate significant advancements in research synthesis and data analysis. These AI-driven systems efficiently aggregate vast amounts of scientific literature, enabling researchers to quickly identify trends, key findings, and gaps across diverse fields. By leveraging natural language processing and machine learning algorithms, tools such as Scopus-AI facilitate enhanced literature review processes and support evidence-based decision-making. Collectively, these Gen-AI applications are revolutionizing the way academic knowledge is curated, interpreted, and utilized, leading to more informed and accelerated scientific discovery [70].

Nanocellulose (NC) is emerging as a highly versatile and sustainable nanomaterial derived from natural sources such as plants, algae, and certain bacteria. Structurally defined by having at least one dimension in the nanoscale range, nanocellulose combines the inherent characteristics of cellulose with the enhanced functionalities of nanomaterials. There are three primary forms of nanocellulose identified in the literature: cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and bacterial nanocellulose (BNC). Each of these variants offers distinct morphological and functional properties, making them suitable for a broad range of advanced material applications. Notably, nanocellulose materials are recognized for their high mechanical strength, thermal stability, biocompatibility, biodegradability, and exceptionally large surface area, which allows for extensive functionalization and adaptability in various industries [71].

Due to these properties, nanocellulose has found applications in multiple sectors. In the biomedical field, it is used for wound healing, drug delivery systems, tissue engineering, and implantable devices, thanks to its biocompatibility and high water-holding capacity. The food industry utilizes it as a stabilizer in emulsions, in packaging materials, and as a source of dietary fiber. Nanocellulose also plays a crucial role in sustainable packaging solutions by enhancing both mechanical and barrier properties, while maintaining biodegradability. In electronics, it contributes to the development of optoelectronic devices and sensors due to its flexibility and unique physical behavior. Environmental applications include its use in water purification systems and as a renewable reinforcing agent in polymer composites. Despite its promising applications, current production methods still face challenges related to energy consumption and processing time. Nonetheless, advancements such as enzymatic processing and microwave-assisted methods are being explored to improve efficiency and sustainability, positioning nanocellulose as a key material in future green technologies and sustainable development efforts [72].

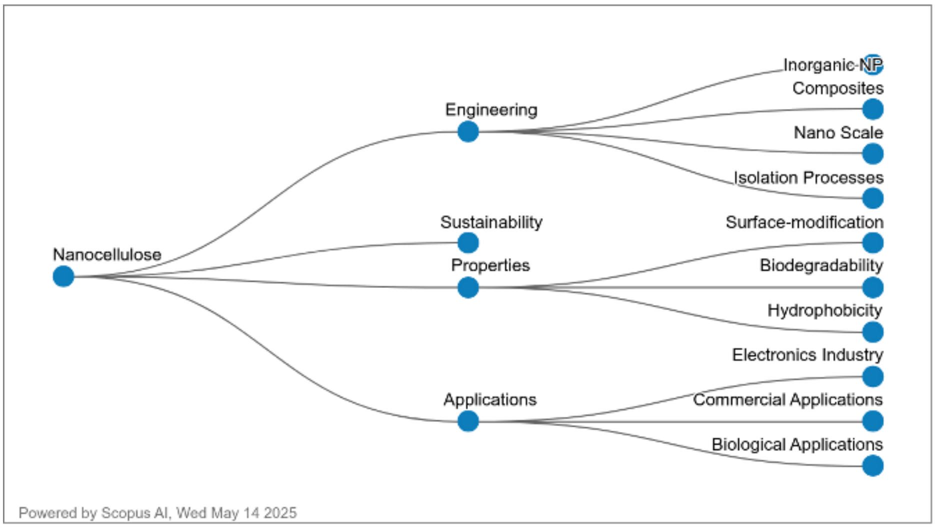


Figure 23. Concept map from Scopus-AI

The diagram in Figure 23 illustrates the diverse research landscape surrounding nanocellulose, highlighting its multifaceted applications and properties across various domains. At the core, nanocellulose branches into key areas such as engineering, sustainability, properties, and applications. Within engineering, topics like inorganic NP composites and nano scale are explored, emphasizing nanocellulose's structural enhancements and minute precision. The sustainability branch highlights its biodegradability and hydrophobicity, demonstrating its environmental impact and functional adaptability. Furthermore, the properties section delves into surface modification and isolation processes, indicating ongoing developments in material customization. Lastly, applications range from electronics to biological contexts, showcasing nanocellulose's versatility and relevance in both commercial and scientific fields. This visualization effectively captures the broad and dynamic scope of nanocellulose research, emphasizing its role as a pivotal material in modern innovation [73].

The main findings of this study demonstrate that nanocellulose research is dominated by a small number of countries, institutions, and journals, with China emerging as the most influential contributor. This dominance can be attributed to strong national funding support and strategic prioritization of sustainable materials research. The integration of machine learning reveals that citation dynamics are influenced not only by publication age but also by journal prominence and thematic relevance, although predictive accuracy remains moderate. Compared to previous bibliometric studies that focused solely on descriptive mapping, this study extends the analysis by introducing predictive modeling, which did not address citation forecasting. The main strength of this research lies in its integrated analytical framework, while limitations include reliance on a single database and the relatively short citation window for recent publications.

CONCLUSION

This study provides a comprehensive bibliometric and predictive analysis of nanocellulose research in the materials science domain from 2021 to 2025. The findings reveal dominant publication trends, key contributors, and emerging research themes, with China and high-impact polymer journals playing central roles. Topic modeling highlights the growing emphasis on biomedical, composite, and sustainable applications, while machine learning demonstrates moderate capability in predicting citation behavior. By integrating bibliometric mapping with predictive analytics, this research not only answers the proposed research questions but also offers a forward-looking framework to support strategic decision-making in future nanocellulose research.

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