



Recent trends and future perspectives on ultrasonic-assisted green synthesis of nanocellulose for food applications

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ABSTRACT

Background: The integration of nanotechnology and sustainable processing has increasingly positioned nanocellulose as a renewable and biodegradable material for food-related applications. Among various eco-friendly synthesis approaches, ultrasonic-assisted processing has emerged as an efficient and green technique for enhancing cellulose fibrillation and functionalization. This study presents a systematic and bibliometric review of global research trends on ultrasonic-assisted green synthesis of nanocellulose for food applications between 2015 and 2025. **Methods:** A comprehensive dataset was retrieved from the Scopus database and analyzed following PRISMA guidelines. Bibliometric mapping using VOSviewer and Biblioshiny was performed to visualize publication dynamics, keyword co-occurrences, and collaboration networks. **Findings:** The findings revealed exponential growth in publications, with major research clusters centered on ultrasonic-assisted nanocellulose synthesis and food packaging applications. The systematic review further highlights the advantages of ultrasonication in improving the mechanical strength, optical transparency, thermal stability, crystallinity, biodegradability, and eco-efficiency of nanocellulose compared to conventional methods. **Conclusion:** Despite these advancements, challenges remain regarding process scalability and safety evaluation for food contact applications. Overall, this study identifies current research gaps, emerging directions, and sustainability implications, contributing to the advancement of green nanotechnology in the food sector. **Novelty/Originality of this article:** By combining VOSviewer and Biblioshiny for cross-platform analysis, this study offers a more comprehensive visualization than previous studies that used only a single tool, thereby providing a structured framework for developing environmentally friendly nanocellulose technology.

KEYWORDS: acoustic cavitation; food packaging; nanocellulose; Pickering emulsion; ultrasonication.

1. Introduction

In recent years, the advancement of green synthesis and nanotechnology has become one of the major driving forces in promoting sustainability across the global food sector. This momentum is largely influenced by increasing environmental concerns, the growing awareness of the impact of plastic pollution, and the urgent need for safer, more sustainable alternatives to conventional synthetic materials. As consumers and industries intensify their focus on eco-friendly solutions, researchers have been challenged to develop biodegradable, renewable, and functionally superior materials that can meet the rigorous requirements of modern food systems. Consequently, the exploration of bio-based

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nanomaterials has expanded significantly, and among these candidates, nanocellulose has gained remarkable attention due to its versatility, abundance, and highly desirable physicochemical properties (Qanitah et al., 2025).

Cellulose itself is a naturally occurring biopolymer composed of β -D-glucopyranose units linked through β -1,4-glycosidic bonds. When this biopolymer is processed into nanoscale dimensions, typically characterized by diameters below 100 nm and lengths under 1000 nm, it is referred to as nanocellulose, a class of materials that exhibits properties markedly different from those of its bulk counterpart (Wang et al., 2021). The nanoscale structure results in unique advantages such as an exceptionally high surface area, high aspect ratio, superior mechanical strength, enhanced stiffness, and increased surface reactivity. Additionally, nanocellulose exhibits attractive optical characteristics, including translucency or even transparency, depending on the production method and morphological (Ji et al., 2023). These features collectively expand its range of potential applications and enable its integration into advanced materials that require a combination of biocompatibility, structural integrity, and sustainability.

Nanocellulose has been widely explored in various multidisciplinary fields. In biomedical science, it has been studied for drug delivery systems, wound dressings, protein carriers, and tissue engineering scaffolds due to its biocompatibility, hydrophilicity, and tunable surface chemistry. In material science, nanocellulose contributes to the reinforcement of composite structures, enhancing the mechanical performance of polymer blends, paper-based products, and structural composites. Emerging applications in energy and electronics, such as supercapacitors, conductive films, sensors, and template materials, further highlight the material's ability to bridge the gap between sustainability and high-performance functionality. Moreover, in environmental engineering, nanocellulose has shown exceptional potential for wastewater treatment through its ability to act as an adsorbent, flocculant, or structural component in cellulose aerogels for capturing contaminants and heavy metals. The integration of nanocellulose into the food industry, one of the most rapidly expanding areas of research has demonstrated its versatility in improving food formulations, stabilizing emulsions, encapsulating bioactive compounds, and enhancing packaging systems (Zhang et al., 2023).

Within the food sector, the adoption of nanocellulose has been particularly promising due to the stringent requirements for safety, stability, and environmental friendliness. Researchers have shown that nanocellulose can serve as an efficient stabilizer in emulsion-based food systems, functioning within the principles of Pickering stabilization through the formation of solid particle-based interfacial layers (Saelices & Capron, 2018; Lu et al., 2021). Its ability to enhance emulsion stability without relying on synthetic surfactants is highly relevant to the growing demand for clean-label and additive-free food products. Additionally, the high surface area and tunable surface chemistry of nanocellulose allow it to act as a carrier for bioactive ingredients, enabling controlled or targeted release, improved solubility, and enhanced protection of sensitive compounds during processing and storage (Baek et al., 2021).

Beyond formulation applications, nanocellulose has gained significant traction in the development of environmentally responsible food packaging systems. Studies have reported the synthesis of green nanofilms (Udayakumar & Anguraj, 2025), nanocomposite films designed for preserving highly perishable fruits such as strawberries and mushrooms (Bacha et al., 2025a), and active packaging materials capable of extending shelf life through antimicrobial or antioxidant functionalities (Yang et al., 2025). The emerging field of smart packaging further expands nanocellulose's usefulness, with examples such as freshness indicators for shrimp products based on nanocellulose based sensors (Xu et al., 2024). Additionally, nanocellulose has been proposed as a potential fat replacer in low-fat food formulations, where its rheological properties can mimic the creaminess and mouthfeel of lipid fractions without contributing to caloric density or compromising nutritional quality (Asghari et al., 2021). These developments collectively illustrate the material's broad potential to transform food processing, quality enhancement, and packaging sustainability.

Among the various techniques used to produce nanocellulose, green synthesis approaches have gained increasing interest due to their alignment with environmental and economic priorities. Traditional extraction and cellulosic nanostructure fabrication methods often involve intensive mechanical processes or harsh chemical agents, which can impose environmental burdens or increase production costs. To address these limitations, researchers have explored greener and more energy-efficient technologies that minimize chemical waste, reduce processing time, and lower environmental impacts.

Ultrasonication is one of the most promising techniques within this context. Ultrasonic-assisted synthesis operates through the generation of acoustic cavitation, rapid formation, growth, and collapse of microbubbles in a liquid medium, which produces intense shear forces that facilitate the disintegration of cellulose fibers into nanoscale components. Compared to conventional chemical or mechanical treatments, ultrasonication offers substantial benefits including reduced energy consumption, shorter processing durations, and minimized need for corrosive or hazardous chemical reagents (Ji et al., 2023). These advantages make ultrasonication a more sustainable and cost-effective approach, consistent with the principles of green chemistry and sustainable processing. Furthermore, ultrasonic treatment contributes to modifications in the morphology and crystallinity of nanocellulose, which in turn affects its functional performance in food applications. Several studies have underlined its potential to improve yield, increase homogeneity, and preserve structural integrity while maintaining environmentally friendly processing characteristics (Abdo et al., 2023; Ji et al., 2023).

Despite the rapid increase in scientific interest and the growing number of publications addressing ultrasonic-assisted nanocellulose synthesis, several important gaps remain in the current research landscape. Although individual studies have explored the technical, functional, and application-specific aspects of nanocellulose, there has not yet been a comprehensive effort to integrate these findings into a cohesive, large-scale mapping of global research trends. In particular, there is a lack of bibliometric and systematic analyses that examine research trajectories, collaborative networks, thematic clusters, and emerging fronts within the field of ultrasonic-assisted nanocellulose production specifically for food-related applications.

Therefore, to address this gap, the present study aims to systematically and bibliometrically analyze global research trends, thematic developments, and emerging applications associated with ultrasonic-assisted green synthesis of nanocellulose in the food industry from 2015 to 2025. By combining systematic review methodologies with bibliometric mapping, this study seeks to clarify the scientific evolution of this topic, identify influential authors and institutions, quantitatively assess the growth of the field, and highlight prominent research themes and technological advancements. The outcomes of this analysis are expected to offer valuable insights for researchers, industry practitioners, and policymakers. More importantly, the findings will help identify future research opportunities and guide the development of sustainable, high-performance nanocellulose-based materials tailored for food applications, ultimately contributing to the broader goals of environmental sustainability and innovation in food nanotechnology.

2. Methods

This study employed a combined methodological framework consisting of bibliometric analysis and systematic review to obtain a comprehensive understanding of scientific developments related to ultrasonic-assisted green synthesis of nanocellulose for food applications. The integration of these two approaches enables a holistic assessment of the research landscape. Bibliometrics provides quantitative insights into publication patterns and scholarly influence, while the systematic review generates in-depth qualitative interpretations of research findings. Together, these complementary methods serve to strengthen the robustness, reliability, and interpretative depth of the study.

2.1 Data source and search strategy

The data was collected from Scopus database, which is widely recognized as one of the largest and most reputable sources of peer-reviewed scientific literature. Scopus offers extensive coverage across multidisciplinary fields, including engineering, material science, chemistry, food science, and nanotechnology, which collectively form the core knowledge domains associated with this research topic. To ensure consistency and minimize temporal bias caused by continuous database updates, all searches were conducted on a single day, 13 October 2025. Conducting searches on a fixed date is an established best practice in bibliometric research, as it prevents variations in publication counts, indexing status, or citation metrics from occurring during data retrieval.

The search string was constructed to capture studies explicitly related to nanocellulose, ultrasonic or sonication-based processing, and food sector applications. The search terms used were:

TITLE-ABS-KEY (Nanocellulose) OR (Cellulose Nano) AND (Sonication*) OR (Ultrasound) OR (Ultrasonic*) AND (Food*).

The data then selected focusing on publication years between 2015-2025, limited to document type article and review, final publication stage, and English language publication.

2.2 Data cleaning, screening, and refinement

After extracting the dataset from Scopus, the records were exported in CSV format to facilitate systematic organization and preprocessing. Microsoft Excel was used as the initial platform to screen and remove corrupted entries, incomplete bibliographic fields, and duplicate records. To further enhance data integrity, the refined dataset was imported into Openrefine software (version 3.7.9). The use of OpenRefine ensured that inconsistencies such as misspellings, formatting variations, or duplicated keywords were corrected systematically. After the cleaning and standardization process, the final dataset consisted of 109 documents, which served as the primary source for bibliometric mapping and systematic analysis. Figure 1 presents a schematic overview of the bibliometric workflow, illustrating each stage from data collection to refinement and visualization.

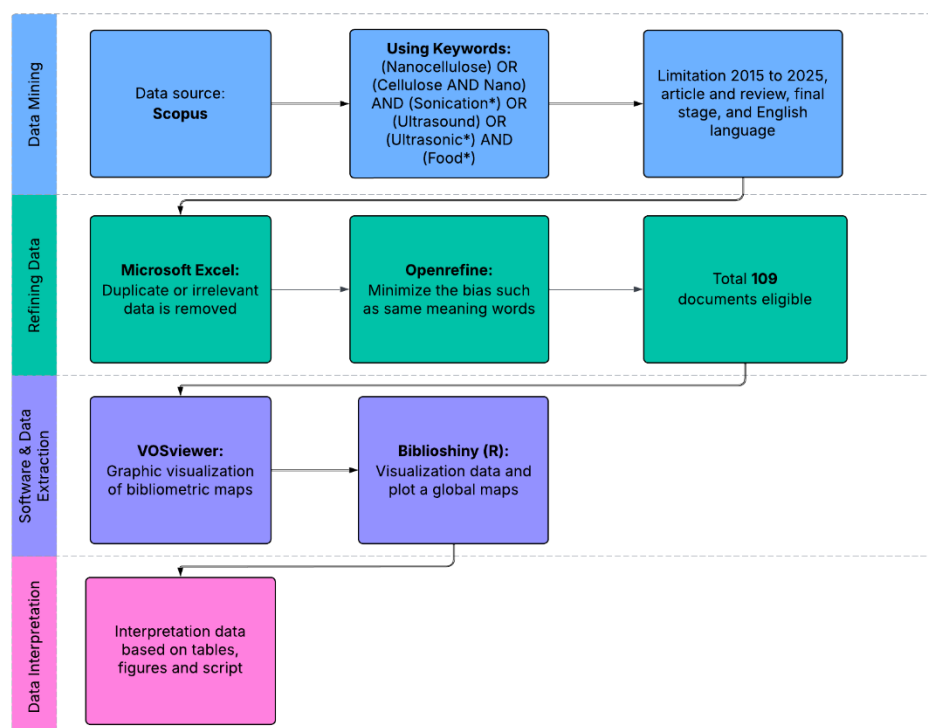


Fig. 1. Flowchart of the bibliometric analysis

2.3 Bibliometric analysis and visualization tools

Bibliometric analysis serves as a quantitative tool for analysing scientific publications, notably journal articles. Bibliometric analysis aims to analyse research trends, track the impact of articles and authors, and predict future research potential (Dirpan et al., 2023a). Bibliographic analysis can help researchers identify areas of study and collaborate with academic colleagues. In this study, bibliometric analysis was employed to extract metrics related to publication year distribution, journal sources, keyword frequency, countries of origin, and institutional affiliations. These metrics collectively provide a comprehensive understanding of the evolution and structure of research on ultrasonic-assisted nanocellulose. VOSviewer (v. 1.6.20) software was used to create bibliometric graphical mapping and network visualization using the most frequent terms, countries, affiliations, and journals that contribute the most and are interrelated. Meanwhile, Biblioshiny R (v. 5.0) was used to visualize the analyzed data and plot a global map showing the geographic distribution of articles.

2.4 Systematic review approach

Following the quantitative bibliometric analysis, a systematic review was conducted to synthesize research findings from the selected publications. Systematic review methods are widely regarded as rigorous and transparent processes for collecting, evaluating, and interpreting existing evidence in a structured manner. This approach allowed the study not only to map trends but also to interpret how ultrasonic-assisted green synthesis of nanocellulose has been practically implemented, optimized, and applied in food-related contexts.

Systematic review analysis incorporates multiple stages, such as developing research results, assessing evidence quality, and evaluating conclusions. The titles and abstracts of the search results were initially assessed according to the predefined eligibility criteria by a single reviewer. Articles that met the initial criteria proceeded to full-text assessment to confirm their relevance and eligibility. During the qualitative screening stage, full-text articles were assessed based on four main parameters: (i) the use or production of nanocellulose, (ii) the application of ultrasonication, sonication, or ultrasound-assisted processing, (iii) the reported processing, physicochemical, or functional outcomes, and (iv) relevance to food-related applications. Articles that did not meet these relevance criteria were excluded from the systematic review. The inclusion criteria are as follows: studies published between 2015 and 2025; works that had reached the final publication stage; articles written in English; and documents categorized as research articles or reviews. While the exclusion criteria are as follows: Publications in languages other than English; theses, dissertations, books, book chapters, conference proceedings, and other forms of gray literature. Figure 2 is displayed a flow diagram summarizing the article selection procedure in accordance with the PRISMA guidelines (Page et al., 2021).

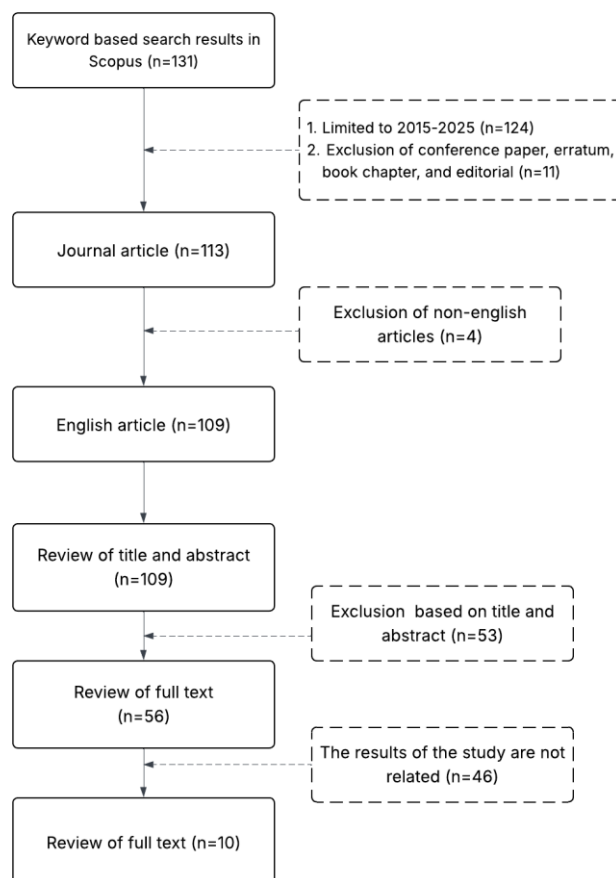


Fig. 2. Flowchart article selection procedure following PRISMA method

3. Results and Discussion

3.1 General performances of selected publications in the research field

Figure 3 shows the distribution and characteristics of journal articles incorporated in the investigation of ultrasonic-assisted green synthesis of nanocellulose for food applications. A total of 109 documents were extracted from the Scopus database, comprising 97 original research articles and 12 review papers, published across 60 distinct journal sources. The diversity of document types and publication outlets demonstrates the broad scientific interest in this topic, particularly within the fields of food science, materials engineering, and sustainable processing technologies. Temporal analysis reveals a consistent increase in publication output over the past decade, with research activity reaching its highest level in 2024. This upward progression indicates the growing recognition of nanocellulose as a promising, eco-friendly material within the food industry.

Citation dynamics further support this trend. The highest annual citation count was recorded in 2020, amounting to 870 citations. This suggests that seminal studies published around this period provided a substantial foundation for subsequent research developments. The increasing rate of publications and citations aligns with global scientific efforts to advance sustainable production practices and develop functional, bio-based materials for food-related applications (Flores et al., 2025). Within this context, ultrasonic-assisted synthesis has emerged as one of the most advantageous approaches due to its efficiency, reduced processing time, and lower environmental impact compared with conventional chemical methods. Ultrasonication is widely acknowledged as a green processing technology capable of enhancing cellulose fibrillation while minimizing solvent usage, toxic by-products, and overall waste generation (Hussain et al., 2025). Taken together, the data presented in Figure 3 indicate that the field of ultrasonic-assisted green

synthesis of nanocellulose is experiencing substantial and sustained growth. The increasing scholarly engagement suggests that this method is gaining significant scientific attention and is expected to continue expanding in the forthcoming years. This momentum is driven by the rising demand for environmentally responsible processing technologies and the potential of nanocellulose to improve functionality, stability, and performance in various food applications. The continued evolution of this research domain is likely to foster new insights, methodological advancements, and broader industrial implementation.

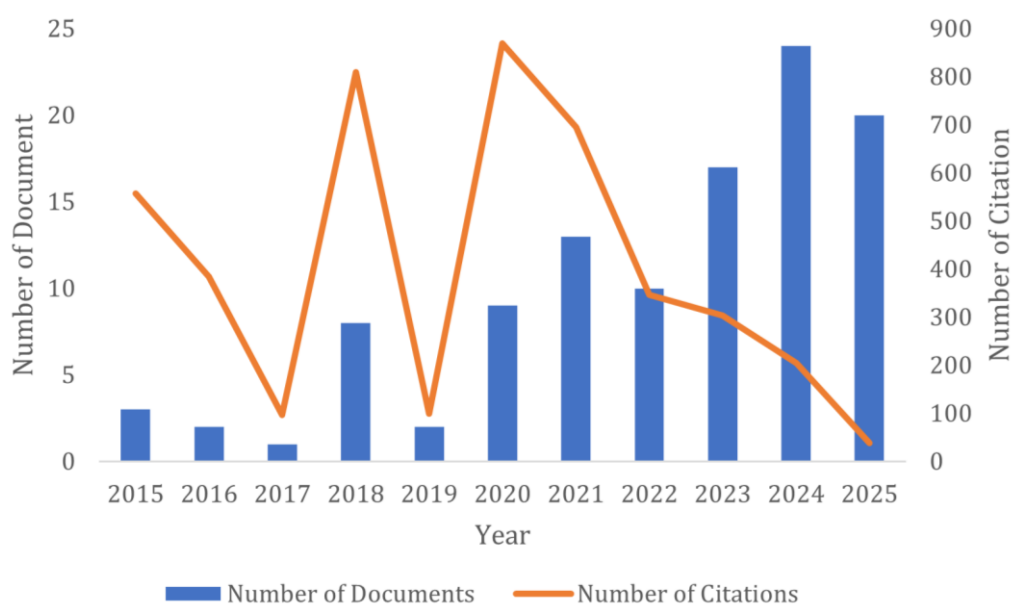


Fig. 3. Number of publications and citations on ultrasonic-assisted green synthesis of nanocellulose for food applications

3.2 Bibliometric analysis of most productive and most-cited journals

The data presented in the Table 1 show the top 15 of sources publishing journals based on their level of relevance to ultrasonic-assisted green synthesis of nanocellulose for food applications. In addition, the table also shows the h-index and quartile values, which serve as indicators for determining a journal's impact within the scientific community in the development of this topic. Based on the eligible data, among 109 articles published between 2015 and 2025, a total of 60 different publishing sources were identified. The International Journal of Biological Macromolecules ranks first, with 22 published articles. This predominance can be attributed to the journal's strong relevance to the topic, as it focuses on biological macromolecules such as cellulose. In second place is Carbohydrate Polymers, with a total of 11 published articles.

Regarding citation performance, Carbohydrate Polymers achieved the highest citation count, with 971 citations from 11 published documents, followed by the International Journal of Biological Macromolecules, which received 703 citations from 22 documents. Study by Kim et al. (2015) is the most highly cited publication, a the review article titled "Preparation, characterization and utilization of starch nanoparticles", which has accumulated 387 citations. The second most cited work is "Preparation of nanocellulose from microcrystalline cellulose, a study by Shankar & Rhim (2016) found the effect on the performance and properties of agar-based composite films," with 342 citations. The third most cited article is a study by Abiral et al. (2020), "Transparent and antimicrobial cellulose film from ginger nanofiber", received 262 citations, followed by the review "Cellulose from sources to nanocellulose and an overview of synthesis and properties of nanocellulose/zinc oxide nanocomposite materials" with 214 citations. The fifth most cited article "Design and

preparation of antimicrobial meat wrapping nanopaper with bacterial cellulose and postbiotics of lactic acid bacteria” (Shafipour Yordshahi et al., 2020) has 152 citations.

The h-index value of a journal reflects the degree of relevance and the overall scientific influence of its publications (Dirpan,et al., 2023b). In terms of h-index, Scientific Reports recorded the highest score (347), followed by Carbohydrate Polymers (294).

Table 1. The trend of the 15 most productive sources publishing article in the field of ultrasonic-assisted green synthesis of nanocellulose for food applications

No	Sources	TP ^a	Publisher	H-index ^b	Q ^c	Total Citation
1	International Journal of Biological Macromolecules	22	Elsevier BV	219	1	703
2	Carbohydrate Polymers	11	Elsevier BV	294	1	971
3	Food Hydrocolloids	4	Elsevier BV	235	1	325
4	Polymers	4	MDPI	167	1	80
5	Food Research International	3	Elsevier BV	231	1	119
6	Industrial Crops and Products	3	Elsevier BV	186	1	186
7	Biomass Conversion and Biorefinery	2	Springer Verlag	56	2	19
8	Bioresources	2	North Carolina State University	104	3	4
9	Frontiers in Chemistry	2	Frontiers Media SA	121	1	124
10	Nanomaterials	2	MDPI	151	1	23
11	Rsc Advances	2	Royal Society of Chemistry	230	1	42
12	Scientific Reports	2	Nature Research	347	1	97
13	Trends in Food Science and Technology	2	Elsevier BV	271	1	126
14	Waste and Biomass Valorization	2	Springer Science and Business Media B.V.	79	2	8
15	ACS Omega	1	American Chemical Society	120	1	1

Note: (a) Total publication of the journals 2015-2025, (b) Journal's h-index in the scopus data, (c) Quartile based on Scimago report 2025.

3.3 Bibliometric analysis of author's production over time

A total of 109 articles authored by 577 researchers were analyzed. The top 10 most productive authors in the field of ultrasonic-assisted green synthesis of nanocellulose for food applications are listed in Table 2. The analysis of author productivity and citation impact was performed using the Bibliometrix package in RStudio, with the h-index used as an indicator of research contribution and scholarly achievement. Although the h-index provides insight into a researcher's influence, it may not accurately reflect performance across different disciplines (Okaiyeto et al., 2020). Citation counts, on the other hand, can be used to measure an author's impact within a specific research domain. As shown in Table 2, Abrial hairul was identified as the most prolific contributor in this area, with five publications and a total of 548 citations, followed by Mahardika Melbi, who also produced five publications with the same citation count.

Abrial Hairul's research primarily focuses on the utilization of cellulose derived from natural sources, particularly from ginger. His studies have explored its application in the development of edible films, emphasizing the characterization of their physicochemical properties (Abrial et al., 2020), antibacterial performance (Abrial et al., 2021), and its role as a reinforcing agent in bionanocomposites (Asrofi et al., 2018).

Table 2. Top ten authors who participated the most in studies on ultrasonic-assisted green synthesis of nanocellulose for food applications

No	Authors	H-index	Total Citation	Documents	PY_Start
1	Abral hairul	5	548	5	2018
2	Mahardika melbi	5	548	5	2018
3	Aminah ibtisamatul	3	401	3	2020
4	Handayani dian	3	401	3	2020
5	Mcclements david julian	3	170	3	2021
6	Sandrawati neny	3	401	3	2020
7	Wu changling	3	170	3	2021
8	Ariksa jeri	2	298	2	2020
9	Asrofi mochamad	2	147	2	2018
10	Costa ana letícia rodrigues	2	199	2	2018

3.4 Bibliometric analysis of country performance

The number of publications produced by a country broadly reflects the productivity, research capacity, and distribution of scholars contributing to a particular scientific topic. It also indicates the strategic prioritization of specific research areas within national science and technology agendas. As illustrated in Figure 4, a total of 32 countries across multiple continents have actively contributed to research on the ultrasonic-assisted green synthesis of nanocellulose for food applications, demonstrating the global relevance and interdisciplinary nature of this emerging field.

Among these contributing nations, China recorded the highest number of publications ($n = 220$), positioning it as the most influential and productive country in this research domain. China is followed, though at a considerable distance, by India ($n = 50$), Brazil ($n = 43$), Indonesia ($n = 43$), and Malaysia ($n = 30$). This distribution suggests a strong research presence not only in Asia but also in South America, highlighting that interest in green nanotechnology and sustainable food materials is not limited to traditionally dominant scientific regions.

China's remarkable dominance in publication output can be attributed to several interrelated factors. First, the country has heavily invested in strengthening its research infrastructure, resulting in a high concentration of experts specializing in nanotechnology, material science, biomaterials, and food engineering. Second, China's national research priorities increasingly emphasize sustainability, circular bioeconomy development, and environmentally friendly manufacturing technologies, areas that align closely with the principles of green nanocellulose synthesis. Third, China has established extensive networks of collaboration between universities, governmental research institutes, and industry partners. These collaborative structures facilitate the rapid translation of fundamental research into technological innovation.

Additionally, the food industry in China has shown robust interest in integrating nanocellulose-based functional materials into product development. Many companies are exploring nanocellulose for applications such as food stabilization, smart packaging systems, functional ingredients, and environmentally responsible processing technologies. This industrial engagement has further stimulated academic research activity, creating a mutually reinforcing cycle between market demand and scientific (Jiang et al., 2025; Pei et al., 2025; Wang et al., 2025). The combination of strong government support, industrial relevance, and a highly active scientific community collectively positions China at the forefront of global research efforts in ultrasonic-assisted green nanocellulose synthesis for food applications.

In addition, countries such as India, Brazil, Indonesia, and Malaysia also contribute a growing number of publications and exhibit notable upward trends in this research area. Their increasing research output highlights emerging national priorities in sustainable natural resource utilization, supported by the abundant availability of plant biomass suitable for nanocellulose production. These countries often rely on agricultural-based economies, making nanocellulose a strategically valuable material for added-value bioproduct development. Furthermore, the increasing emphasis on environmentally friendly food packaging and the reduction of plastic waste in these regions provides

additional momentum for continued research in ultrasonic-assisted nanocellulose synthesis.

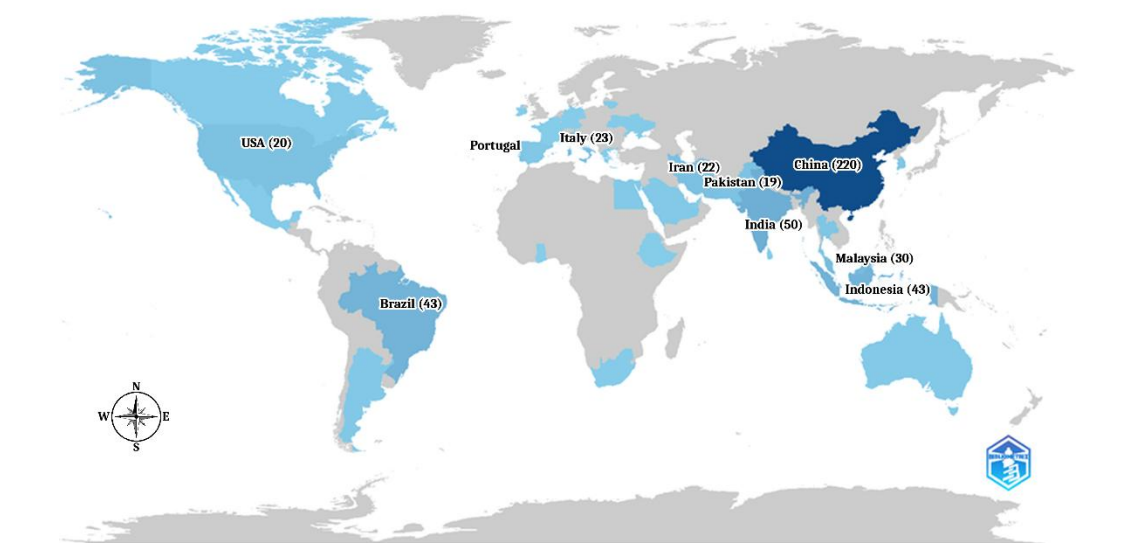


Fig. 4. Country scientific production on ultrasonic-assisted green synthesis of nanocellulose for food application from 2015 to 2025

3.5 Co-occurrence network analysis of author keywords

Co-occurrence analysis is a technique used to visualize the relationships between author keywords within journals or articles. This analysis helps identify the most frequently used keywords, as well as those that are less commonly associated with the topic. Furthermore, evaluating the co-occurrence network of author keywords enables researchers to gain a more comprehensive understanding of the thematic structure and research trends related to the subject (Dirpan, et al., 2023a).

Table 3. The most used keywords based on occurrences and total link strength

No	Keywords	Occurrences	Total link strength
1	Nanocellulose	27	23
2	Ultrasonication	19	15
3	Pickering emulsion	11	11
4	Cellulose	7	8
5	Mechanical properties	4	8
6	Rheology	3	7
7	Stability	4	7
8	Cellulose nanocrystals	8	6
9	Chitosan	4	6
10	Food packaging	4	6
11	High-pressure homogenization	3	6
12	Active packaging	4	5
13	Antibacterial	4	5
14	Bacterial nanocellulose	3	5
15	Biodegradable	3	5
16	Composite film	3	5
17	Nanocellulose hydrogel	3	5
18	Okara	3	5
19	Sonication	4	5
20	Crystallinity	3	4

Overall, these five clusters are thematically interconnected, illustrating a comprehensive research continuum ranging from nanocellulose synthesis and characterization (Clusters 2 and 4) to material development (Cluster 5) and functional

applications in active packaging and bioactive delivery systems (Clusters 1 and 3). This interconnection underscores the current trend toward sustainable, application-oriented innovation in nanocellulose research, driven by ultrasonic-assisted green synthesis technologies.

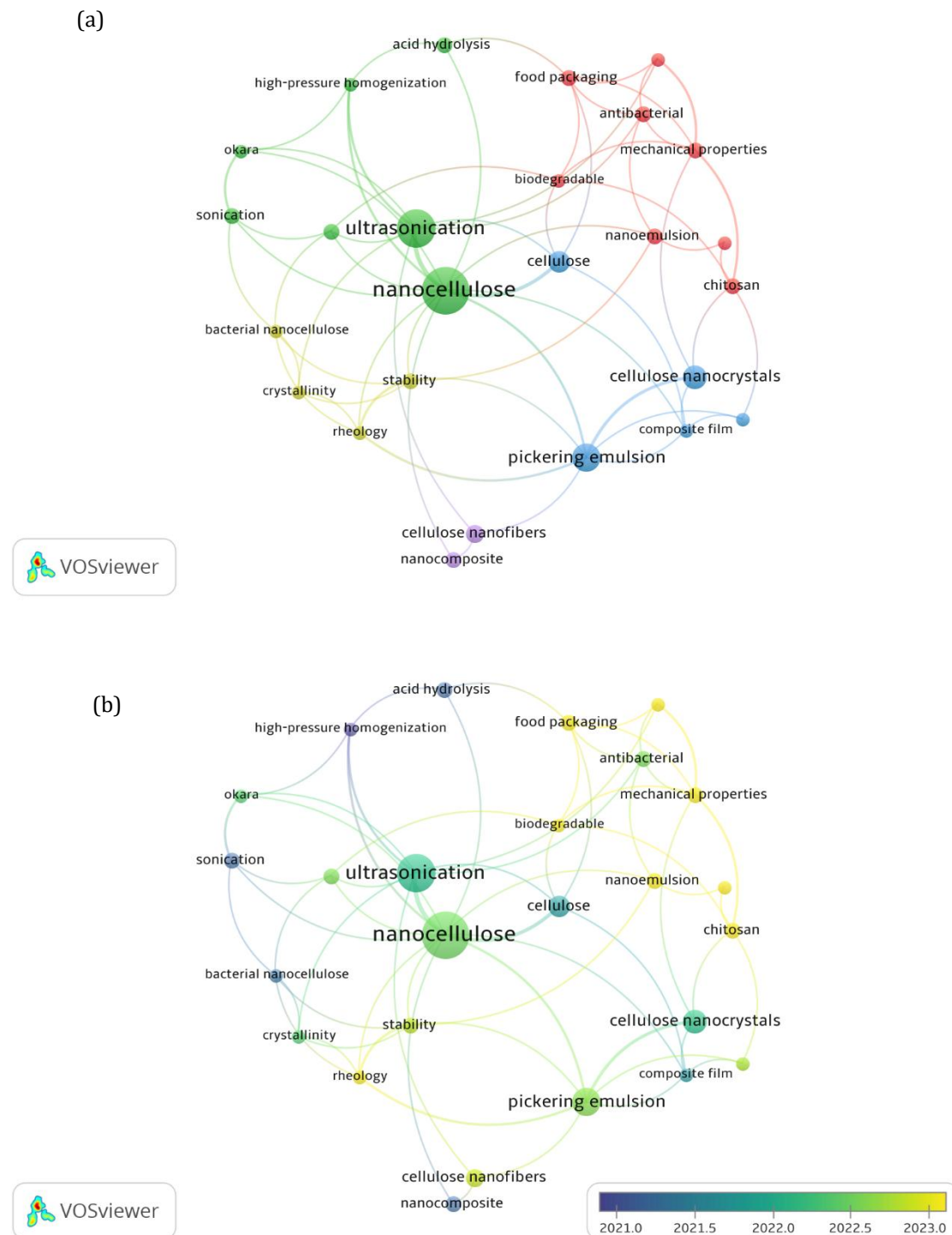


Fig. 5. Co-occurrence network: author keywords used in ultrasonic-assisted green synthesis of nanocellulose for food application articles (a) and author keyword articles in the field of ultrasonic-assisted green synthesis of nanocellulose for food application (b) from 2015 to 2025

In this study, a co-occurrence network analysis of author keywords was visualized using VOSviewer (Figure 5a and 5b). The minimum keyword occurrence was set at 3, and among the 370 identified keywords, only 26 met the threshold, resulting in a total link

strength of 82. The co-occurrence network analysis of author keywords shown in Figure 5a was conducted to assess the degree of association among terms related to ultrasonic-assisted green synthesis of nanocellulose for food applications. Table 3 presents the top 20 keywords used over the last decade, based on their total occurrences and link strength. The most frequently appearing keywords were nanocellulose, ultrasonication, Pickering emulsion, cellulose, and mechanical properties, with 27, 19, 11, 7, and 4 occurrences, respectively, and total link strengths of 23, 15, 11, 8, and 8. The network was divided into five clusters, each represented by a different color. Each cluster illustrates groups of interrelated keywords that frequently co-occur in scientific publications, while the size of each circle reflects the number of publications using that keyword—the larger the circle, the higher the frequency of occurrence. The color of the circle represents the relationships and proximity between keywords within the network (Hu et al., 2013).

Based on Figure 5a, Cluster 1 (red) represents the most dominant group, consisting of eight keywords: antibacterial, biodegradable, carboxymethylcellulose, chitosan, food packaging, mechanical properties, nanocellulose hydrogel, and nanoemulsion. This cluster reflects a strong research focus on the application of biopolymers in active and environmentally friendly food packaging systems. The combination of nanocellulose with natural materials such as chitosan (Yadav et al., 2024) and carboxymethylcellulose (Bacha et al., 2025b) materials with enhanced mechanical properties, biodegradability, and antimicrobial activity through the integration of hydrogel (Wu et al., 2024; Yu et al., 2024) or nanoemulsion systems (Begum et al., 2024; Sun et al., 2025).

Cluster 2 (green) comprises seven keywords: acid hydrolysis, active packaging, high-pressure homogenizer, nanocellulose, okara, sonication, and ultrasonication. This cluster is associated with the synthesis and production of nanocellulose through environmentally friendly physicochemical approaches. The use of ultrasonication and high-pressure homogenization techniques facilitates the disintegration of cellulose fibers derived from biomass sources such as okara, producing nanocellulose with homogeneous dispersion and high purity (Wu et al., 2021). The synthesized nanocellulose is subsequently applied in active food packaging systems, as reflected in the first cluster.

Cluster 3 (blue) includes five keywords: cellulose, cellulose nanocrystals, composite film, curcumin, and Pickering emulsion. This cluster focuses on the utilization of nanocellulose as a stabilizer and reinforcing agent in emulsion or composite film systems. Studies within this cluster highlight the role of cellulose nanocrystals (CNC) in stabilizing Pickering emulsions without the use of synthetic surfactants (Yazid et al., 2025) and enhancing the stability of bioactive compounds such as curcumin in active food delivery systems (Tran et al., 2021).

Cluster 4 (yellow), consisting of four keywords: bacterial nanocellulose, crystallinity, rheology, and stability, represents fundamental research on the structural characterization and physicochemical properties of nanocellulose, particularly bacterial nanocellulose (BNC). This cluster explores the relationship between crystallinity, rheological behavior, and material stability, providing essential insights into the performance and functionality of nanocellulose-based systems in food and pharmaceutical applications (Balquinta et al., 2020).

Cluster 5 (purple) consists of two keywords (cellulose nanofibers and nanocomposite), emphasizing the development of nanocomposite-based materials utilizing cellulose nanofibers (CNF) as reinforcing agents (Adam et al., 2022; Balquinta et al., 2020). CNF enhance the mechanical strength, flexibility, and stability of composite materials, making them highly promising for applications in packaging (Tang et al., 2024) and bioactive delivery systems (Hassan et al., 2022).

In addition, figure 5b shows the development of keywords from the last decade. The visual representation of term co-occurrence across time revealed potential areas for further research. Purple nodes represent commonly used keywords in earlier research, whereas yellow nodes represent the new term that were studied by researchers. Based on the illustration in figure 5b, The central and most prominent nodes, nanocellulose and ultrasonication, highlight their pivotal role as core research themes, suggesting that the

integration of ultrasonic technology in the synthesis and processing of nanocellulose is a dominant and connecting topic across the literature. The keywords displayed in bright yellow on the temporal color scale represent the most recent research topics. These keywords include food packaging, antibacterial, biodegradable, mechanical properties, nanoemulsion, nanocellulose hydrogel and chitosan. The predominance of yellow nodes in this area indicates a clear shift in research focus, from the fundamental synthesis and characterization of nanocellulose toward its practical applications in food systems.

3.6 Systematic review findings

A systematic review of selected studies was conducted to identify trends, methodologies, and applications of ultrasonic-assisted nanocellulose synthesis in the food sector. The findings were grouped into four main themes: synthesis parameters, material characterization, key findings, and food-related applications. As summarized in Table 4, recent research has utilized diverse biomass sources, such as ginger fiber, coconut pomace, bamboo, and ginkgo seed shells. These studies consistently emphasize sustainable extraction and modification methods that combine ultrasonication with chemical, enzymatic, or deep eutectic solvent (DES) treatments to enhance nanocellulose yield, structural homogeneity, and functionality (Abraal et al., 2020; Ni et al., 2022; Wang et al., 2025).

Materials obtained through ultrasonication exhibit enhanced mechanical strength, optical transparency, thermal stability, and biodegradability compared to those produced by conventional processes. The focus of research has also shifted from basic synthesis and characterization toward practical food-related applications, particularly in active and intelligent packaging, fat-replacement systems, and edible coatings. Furthermore, the development of composite and hybrid materials, such as cellulose nanofibril/TiO₂ and thermoplastic starch–CNF systems, highlights growing interest in multifunctional and sustainable biopolymers for the food industry (Dungani et al., 2025).

3.7 Research gaps and future perspectives

Ultrasonication has emerged as a promising sustainable technique for nanocellulose synthesis offering advantages in energy efficiency and environmental compatibility. The bibliometric and systematic findings of this review indicate a clear and growing research interest in combining ultrasonication with nanocellulose for food related applications, particularly biodegradable and functional food packaging. However, several critical research gaps must be addressed before this technology can be translated from laboratory scale studies to industrial applications.

A major limitation is the scalability of ultrasonication based nanocellulose production. The systematic reviewed in this study is still dominated by batch-processing systems, with relatively limited evidence concerning continuous-flow operation. At larger production scales, maintaining uniform acoustic energy distribution, cavitation intensity, residence time, and fibrillation efficiency becomes increasingly challenging. Therefore, future studies should systematically investigate continuous-flow ultrasonic reactors and establish quantitative relationships between ultrasonic power density, frequency, amplitude, treatment time, suspension concentration, and nanocellulose yield and quality. Such studies should also report energy consumption per unit mass of nanocellulose produced to enable meaningful comparisons among ultrasonic and conventional production routes. Process intensification, reactor geometry optimization, and energy-efficient probe or transducer configurations should be prioritized to overcome the limitations associated with scale-up.

Another important gap concerns the safety and regulatory evaluation of nanocellulose intended for food-contact applications. Although nanocellulose is increasingly investigated as a biodegradable packaging material and functional food ingredient, comprehensive assessments of migration, oral exposure, gastrointestinal fate, cytotoxicity, and long-term safety remain limited. Future research should therefore evaluate nanocellulose containing

materials according to relevant food contact requirements established by regulatory authorities such as the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (FDA). Standardized protocols for migration testing, physicochemical characterization, and toxicological assessment would facilitate comparison among studies and provide stronger evidence for regulatory approval and industrial commercialization.

Addressing these scalability, energy efficiency, and safety challenges through continuous-flow ultrasonication, process optimization, and standardized food contact safety assessment will be essential for facilitating the transition of ultrasonic-assisted nanocellulose production from laboratory research to safe, efficient, and commercially viable food applications.

Table 4. Summary of systematic review findings on ultrasonic-assisted nanocellulose synthesis for food applications (2015–2025)

Material sources	Treatment	Ultrasonication parameters	Material characterization	Key findings	Application in foods	Remarks	References
Coconut pomace cellulose (CPC)	Enzymatic hydrolysis + ultrasonication	Power: 210 W; Time: 20 min; Pulse mode: 1 s on / 1 s off	Diameter: 377 nm; Yield: 59.8%	Ultrasonication enhanced surface charge, wettability, and structural flexibility of cellulose	Food-grade Pickering stabilizer for High Internal Phase Emulsion (HIPEs)	Excellent thermal and freeze–thaw stability for β -carotene encapsulation; higher Ultrasonicated Coconut Pomace Cellulose (UCPC) levels reduced free fatty acid release and β -carotene bioaccessibility	(Wang et al., 2025)
Oil palm trunk	Chemical treatment (succinic acid) + ultrasonication	Frequency: 20 kHz; Output power: 50%; Time: 60 min	Diameter: 25–170 nm; Yield: 92.35%	Non-corrosive succinic acid hydrolysis combined with ultrasonication enhanced nanocellulose yield	Antibacterial packaging material	Cellulose nanofibril/TiO ₂ composites improved tensile strength, brightness, and antibacterial activity (<i>E. coli</i> and <i>S. aureus</i>)	(Dungani et al., 2025)
Coconut dregs	Chemical treatment (HCl, 7 M) + ultrasonication	Power: 750 W; Time: 60 min; Solvent: water	Diameter: <150 nm	Transparent films produced from ultrasonically treated cellulose	Food packaging film	The film extended grape freshness more effectively than conventional plastic	(Rahmi et al., 2024)
Bamboo	DES hydrolysis +	240 V; 20 kHz; 2 kW; Pulse mode: 3:1 on/off	Yield: 83.34%; Diameter: 20–40 nm	50% DES hydrolysis provided optimum yield	Reinforcing agent for food packaging	Thermoplastic Starch (TPS) with 5 wt%	(Kesari et al., 2022)

Material sources	Treatment	Ultrasonication parameters	Material characterization	Key findings	Application in foods	Remarks	References
	ultrasonication					Cellulose Nanofibers (CNF) improved tensile strength, thermal stability, and biodegradability (80% degradation in 60 days)	
Ginkgo seed shells	Ultrasonication	Power: 300 W; Probe diameter: 15 mm; Time: 10–90 min	Interfibrillar distance (ξ): 6.05–86.1 nm	Ultrasonic treatment reduced interfibrillar distance, strengthening the gel network	Food-grade Pickering stabilizer for HIPEs	7:3 hydrogel/water ratio produced the most stable HIPEs	(Ni et al., 2022)
Empty palm fruit bunch (EFB)	Chemical treatment (H ₂ SO ₄) + ultrasonication	Power: 700 W; Amplitude: 60%; Time: 5 min	Width: 15 ± 6 nm; Length: 236 ± 49 nm	EFB-derived Cellulose Nanocrystals (CNCs) were excellent particle stabilizers for nanoemulsions	Food stabilizer and edible coating	Pickering nanoemulsion of black cumin seed oil remained stable for 6 months and prevented enzymatic browning in fresh-cut apples	(Foo et al., 2022)
Cotton linter	Chemical treatment (H ₂ SO ₄) + homogenizer + ultrasonication	Power: 300 W; Time: 4 min	Diameter: 89 nm; Crystallinity increased from 60% to 76%; Swelling capacity ↑ 63%	Combined acid hydrolysis and ultrasonication reduced CNC size and improved crystallinity	Food additive (fat substitute)	Cream with CNCs (50:50 oil/shortening) showed improved stability and sensory properties; CNC concentration requires optimization	(Asghari et al., 2021)
Ginkgo seed shells	Chemical treatment (H ₂ SO ₄) + ultrasonication	Power: 1200 W; Frequency: 20 kHz; Output power: 150–600 W; Time: 10–60 min; Pulse mode: 1 s on/off	Diameter: 24 nm; Length: 310 nm; Zeta potential: –42.5 mV; Crystallinity: 58.33%	Prolonged ultrasonication effectively produced nano-sized cellulose and improved hydrophobicity	Food-grade Pickering emulsion stabilizer	Ultrasound enhanced emulsifying ability via particle size reduction and formation of a viscoelastic interfacial film	(Ni et al., 2021)
Ginger fiber	Chemical treatment (HCl) +	Power: 600 W; Time: 60 min;	Diameter: 54.3 nm; Cellulose	Sonicated films exhibited higher optical	Food packaging film	Transparent film with good antimicrobi	(Abral et al., 2020)

Material sources	Treatment	Ultrasonication parameters	Material characterization	Key findings	Application in foods	Remarks	References
	ultrasonication	Solvent: water	content: 88%	transparency than chemically treated cellulose films		al properties and thermal stability	
Pineapple leaf	Chemical treatment (HCl) + ultrasonication	CNF synthesis: 400 W, 60 min; Film synthesis: 600 W, 5 min	Diameter: 68 nm	Nanofibers and bengkoang starch bionanocomposites exhibited superior thermal stability	Food packaging film	2 wt% CNF enhanced tensile strength (+160%), reduced moisture absorption, and improved thermal stability	(Mahardika et al., 2019)

4. Conclusions

The bibliometric and systematic analysis revealed a growing scientific interest in the ultrasonic-assisted green synthesis of nanocellulose for food applications over the past decade. This trend underscores the increasing relevance of sustainable and eco-efficient technologies in the food sector. China emerged as the leading contributor in publication output, while the International Journal of Biological Macromolecules served as the primary outlet for related research. The dominant themes identified, such as nanocellulose, ultrasonication, and their applications in food packaging, stabilizers, fat substitutes, and edible coatings, reflect a strong alignment with global sustainability goals.

Despite this progress, several research priorities remain. Future studies should move beyond conventional batch-processing approaches and increasingly investigate continuous-flow ultrasonication systems to improve process scalability, consistency, and industrial throughput. Particular attention should be given to optimizing ultrasonic frequency, amplitude, energy input, residence time, and reactor configuration while minimizing energy consumption. Furthermore, comprehensive studies on the safety, toxicity, migration behavior, and long-term stability of nanocellulose-based materials are essential to support regulatory approval. Addressing these technological and safety challenges will facilitate the transition from laboratory-scale research toward the industrial implementation of nanocellulose as a safe, sustainable, and high-value material for modern food systems.

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