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Mapping Probiotic Encapsulation Research: A Bibliometric and Thematic Analysis of Functional Food Applications

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ABSTRACT

Probiotic encapsulation has gained significant attention in functional food science as a means to enhance the stability and viability of probiotics during processing, storage, and gastrointestinal transit. This study provides a bibliometric analysis of global research trends in probiotic encapsulation, identifying key contributors, influential publications, and thematic developments. Using the Scopus database, 515 relevant articles were analyzed through Bibliometrix and VOSviewer to map the evolution of this field. The findings indicate a notable increase in research output, particularly after 2015, with a focus on advanced techniques such as microencapsulation and co-encapsulation. Key applications include improving gut health, managing chronic diseases, and integrating probiotics into functional food matrices. Despite these advancements, significant gaps remain, particularly in clinical validation, large-scale production, and the development of sustainable delivery systems. The analysis highlights the interdisciplinary nature of probiotic encapsulation research, involving collaborations across food science, biotechnology, and health sciences. Future research should emphasize innovative technologies, personalized nutrition approaches, and sustainable encapsulation materials to enhance probiotic efficacy and meet growing consumer demands. This study provides a comprehensive roadmap for advancing probiotic encapsulation, ensuring its integration into functional food products and therapeutic applications.

1. INTRODUCTION

Probiotics, defined as live microorganisms that confer health benefits to the host when administered in adequate amounts, have garnered considerable attention for their role in maintaining gut health, enhancing the immune system, and managing various chronic diseases [1, 2]. These microorganisms, including strains of Lactobacillus, Bifidobacterium, and Saccharomyces boulardii, are integral to numerous biological processes, particularly in promoting a balanced gut microbiota [3-5]. The therapeutic potential of probiotics spans a wide range of health conditions, including digestive disorders, immune system modulation, and inflammatory diseases [6-8]. Despite these significant health benefits, the stability and viability of probiotics during food processing, storage, and gastrointestinal transit remain major challenges. Factors such as heat, oxygen, gastric acids, bile salts, and mechanical stress during food processing and digestion can severely compromise the survival of probiotics, thereby diminishing their efficacy [9, 10]. Addressing these challenges is critical to ensure that probiotics can effectively deliver their intended health benefits to the host.

However, in recent years, probiotic encapsulation has emerged as a cutting-edge innovation within the realm of food science and biotechnology, offering a promising solution to overcome these stability challenges. Encapsulation involves enclosing probiotic microorganisms in a protective matrix or coating, which shields them from harmful environmental conditions such as heat, oxygen, gastric acidity, and bile salts during food processing, storage, and gastrointestinal transit [11-14]. This protection ensures that a higher proportion of viable probiotics reaches the gut, where they can exert their therapeutic effects. Encapsulation not only enhances the survival of probiotics but also improves their functional efficacy, bioavailability, and overall effectiveness when incorporated into various food matrices, such as dairy products, fermented foods, and dietary supplements [15-17].

Moreover, the integration of probiotics into functional foods represents a significant advancement in the field of nutrition and health. Functional foods are specifically designed to provide health benefits beyond basic nutrition, targeting specific physiological functions and helping to prevent or manage various health conditions [18, 19]. The growing consumer demand for health-promoting foods has led to an increased interest in functional foods enriched with bioactive components, such as probiotics, prebiotics, polyphenols, and other nutraceuticals [20, 21]. As consumers become more health-conscious and aware of the strong link between diet and disease prevention, functional foods have gained widespread popularity. This trend reflects the shift from a focus on disease treatment to a proactive approach centered around preventive healthcare and holistic wellness.

Functional foods, particularly those containing probiotics, have proven effective in supporting digestive health, modulating the immune system, reducing inflammation, and preventing chronic diseases such as irritable bowel syndrome (IBS), inflammatory bowel disease (IBD), and even certain metabolic disorders [22-24]. Products such as fermented dairy foods, plant-based alternatives, and dietary supplements enriched with probiotics have emerged as essential components of a balanced and health-focused diet. Probiotic-enriched functional foods are now widely regarded as a cornerstone of a personalized nutrition strategy that aims to meet individual health needs and promote long-term well-being [25, 26].

As a result, the rapid growth of the functional food sector has driven significant advancements in encapsulation technologies to enhance the effectiveness of probiotics. Several encapsulation techniques have been developed, including microencapsulation, nanoencapsulation, and co-encapsulation [27-29]. These technologies employ a variety of materials, such as lipids, polysaccharides, proteins, and natural biopolymers, to create protective coatings that improve probiotic survival during food processing, storage, and transit through the gastrointestinal tract [27, 30]. Microencapsulation, for example, involves encasing probiotic microorganisms in microspheres or microcapsules, while nanoencapsulation uses nanoparticles to protect and deliver probiotics with greater precision and efficiency. Co-encapsulation techniques, which combine probiotics with other bioactive components, have also gained attention for their potential synergistic effects in functional food formulations.

One of the most promising developments in encapsulation technologies is the use of natural and biodegradable materials as encapsulating agents. These materials, such as alginate, chitosan, and plant-based proteins, align with the growing consumer demand for sustainable, environmentally friendly, and clean-label products [31, 32]. Natural encapsulants not only offer improved biodegradability but also provide additional health benefits, such as prebiotic effects, which can further enhance the overall functionality of the encapsulated probiotics [33, 34]. Furthermore, these materials can be tailored to improve the controlled release and targeted delivery of probiotics to specific regions within the gastrointestinal tract, thereby maximizing their therapeutic potential.

Despite the significant advancements in probiotic encapsulation technologies, the research landscape remains fragmented, and several critical challenges persist. One of the major obstacles is the gap between laboratory-scale research and industrial-scale implementation. Many encapsulation technologies demonstrate promising results in controlled experimental settings, yet their scalability and commercial viability remain uncertain. While laboratory-based studies often focus on the optimization of encapsulation methods and the selection of appropriate materials, large-scale production processes present unique challenges, including the need for cost-effective, reproducible, and scalable manufacturing methods. Bridging this gap requires extensive collaboration between academic researchers and industry stakeholders to develop efficient, scalable probiotic delivery systems that can be widely adopted in functional food production.

Another significant issue is the limited clinical validation and consumer testing of encapsulated probiotics. While in vitro and in vivo studies provide valuable insights into the functional properties of encapsulated probiotics, there is a notable lack of large-scale, well-controlled clinical trials to confirm the health benefits of these formulations in human populations. The variability in individual responses to probiotics and the complexity of their interactions with the gut microbiota make it challenging to draw definitive conclusions regarding their therapeutic effects. Furthermore, consumer acceptance is a crucial factor that is often overlooked in research. For probiotic-enriched functional foods to succeed in the market, they must not only be effective but also meet consumer preferences in terms of taste, texture, sensory attributes, and convenience. Therefore, understanding consumer perceptions and conducting market studies are essential components of the research and development process for probiotic-enriched functional foods.

The research landscape in probiotic encapsulation is also characterized by a lack of systematic knowledge synthesis. With diverse research approaches, varying encapsulation techniques, and differing areas of focus, it is difficult to gain a comprehensive understanding of the field. Some studies focus on the development of novel encapsulation materials and methods, while others emphasize probiotic stability, bioavailability, or targeted delivery systems. This fragmentation complicates efforts to integrate findings across different research domains and limits the ability to draw generalizable conclusions. A systematic, interdisciplinary approach is needed to bridge these knowledge gaps and foster a more comprehensive understanding of probiotic encapsulation and its applications in functional foods.

To address these challenges and gaps in the research landscape, bibliometric analysis has emerged as a valuable tool for systematically mapping and analyzing trends in probiotic encapsulation research. Bibliometric methods involve the quantitative analysis of scientific literature, enabling researchers to identify key contributors, track thematic evolutions, and examine collaborative networks within the field. Tools such as Bibliometrix, VOSviewer, and other bibliometric platforms provide invaluable insights into the structure, growth, and impact of research on probiotic encapsulation. These tools allow researchers to visualize citation data, identify emerging research areas, and uncover critical gaps that warrant further investigation. By applying bibliometric analysis, it is possible to synthesize the vast body of research on probiotic encapsulation, identify key trends, and propose actionable recommendations for future research directions [35-38].

The objectives of this study are to map the trends in probiotic encapsulation research, identify the most impactful scientific contributions, and highlight existing knowledge gaps. In particular, this article will also examine several key aspects, including the annual scientific production, the most relevant sources, the most contributing authors, affiliations, the most productive countries, the most cited papers globally and locally, thematic evolution, and the future research trajectory. By synthesizing these insights, this study aims to provide a comprehensive overview of the current state of probiotic encapsulation research, offering actionable recommendations for advancing encapsulation technologies in functional foods.

2. METHODOLOGY

To provide a comprehensive analysis of the research landscape surrounding probiotic encapsulation, this study employed a bibliometric approach, leveraging advanced analytical tools and methods to systematically evaluate the relevant literature. The bibliographic data for this study were sourced exclusively from the Scopus database, widely recognized as one of the most authoritative and comprehensive repositories of peer-reviewed academic literature. Scopus was selected due to its extensive coverage of interdisciplinary research, its inclusion of high-quality journals, and its robust citation-tracking capabilities. Compared to other databases such as Web of Science or PubMed, Scopus offers broader coverage, encompassing over 36,000 titles from a wide range of disciplines, including food science, microbiology, biotechnology, and health sciences. Furthermore, Scopus provides detailed metadata, including citation counts and collaboration networks, which are essential for bibliometric analysis [39-41]. This makes Scopus a preferred choice for researchers seeking a holistic and reliable dataset for bibliometric studies.

The search strategy was designed to capture the breadth and depth of research on probiotic encapsulation in the context of functional foods and dietary health. A Boolean query was constructed using specific keywords and logical operators to ensure the inclusion of the most relevant studies. The search terms included: title-abs-key (probiotic encapsulation) or title-abs-key (encapsulated probiotic) and title-abs-key (human food) or title-abs-key (dietary fatty acid) or title-abs-key (high-fat diet) (Figure 1). These terms were selected to encompass key aspects of the research, including probiotic encapsulation techniques, applications in functional foods, and the broader dietary and health contexts in which these studies are applied. Additionally, the search was filtered to include only articles published in English and those published between 2000 and 2025. The search resulted in 515 articles, all of which were deemed relevant to the research scope.

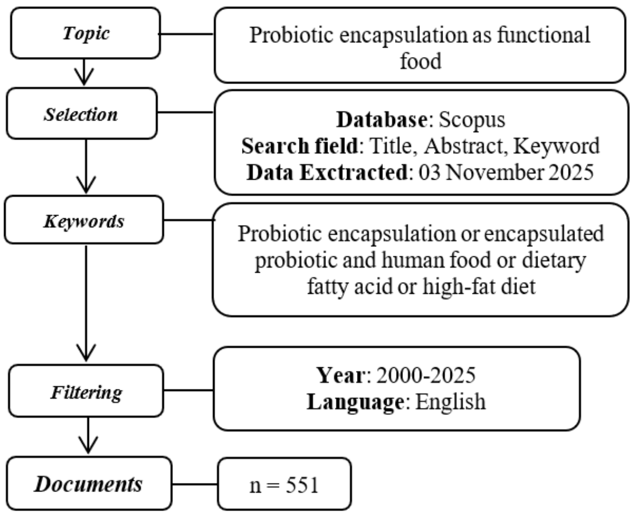


Figure 1. Flowchart of bibliometric analysis

To maintain consistency and minimize potential biases introduced by the dynamic nature of the Scopus database, where content is continuously updated, the search was conducted only once, on November 3, 2024. The resulting dataset was downloaded in BibTeX and CSV formats, providing flexibility in subsequent analyses. The BibTeX format facilitated seamless integration with bibliometric tools like Biblioshiny and VOSviewer, while the CSV format allowed for manual inspection and preprocessing of data to ensure accuracy.

The analysis was conducted using R software version 4.4.1 (R Development Core Team, Vienna, Austria) with the Bibliometrix library version 4.1.3, as well as VOSviewer version 1.6.20. Bibliometrix, an open-source R package, offers a comprehensive suite of tools for performing bibliometric analysis. Its web-based extension, Biblioshiny, was employed for its intuitive user interface, which facilitates interactive data visualization and exploration [37]. Biblioshiny was chosen for its ability to produce detailed analyses on various aspects of the bibliometric data, including:

(1) Source dynamics, such as the number of publications and their growth over time;
(2) Author contributions, identifying the most prolific and influential researchers in the field;
(3) Institutional and country-level analysis, highlighting collaborative networks and geographical trends;
(4) Thematic evolution, providing insights into how research themes have developed and diversified over time.

The use of Biblioshiny allowed for the generation of a variety of visualizations, such as bar charts, Sankey diagrams, and thematic maps, which were essential for interpreting the data and presenting findings comprehensively. In addition to Biblioshiny, VOSviewer was used to construct and visualize bibliometric networks. VOSviewer specializes in creating maps of co-occurrence, co-citation, and bibliographic coupling, making it particularly well-suited for analyzing relationships within the data. In this study, two key analyses were conducted using VOSviewer: 1) Co-occurrence analysis of keywords, which identified the most frequently used terms in the dataset and highlighted emerging research themes. This analysis provided insights into the evolving focus areas within the field of probiotic encapsulation, such as the shift from general encapsulation methods to advanced techniques like microencapsulation and co-encapsulation; 2) Co-citation analysis, which examined the relationships between cited references to identify influential studies and their interconnections. This analysis revealed the foundational works in the field and helped map the intellectual structure of probiotic encapsulation research.

By combining the capabilities of Biblioshiny and VOSviewer, this study was able to provide both macro- and micro-level insights into the research landscape. Biblioshiny's interactive features allowed for a broad exploration of publication trends, key contributors, and thematic developments, while VOSviewer provided a deeper understanding of the relationships between studies and concepts within the field. Together, these tools enabled a comprehensive evaluation of the literature, offering valuable insights into the historical progression, current state, and future directions of probiotic encapsulation research. This systematic approach ensured that the study not only identified critical trends and contributors but also addressed gaps in the existing literature, paving the way for more targeted and impactful research in the future [38, 42].

3. RESULT AND DISCUSSION

In conducting a bibliometric analysis on the topic of probiotic encapsulation in human food, it is essential to systematically examine the comprehensive dataset generated from Biblioshiny, as depicted in the table provided. This bibliometric assessment focuses on published research from the timespan of 2000 to 2025 (Table 1). A total of 231 sources, including journals and books, are analyzed, covering 515 documents, which indicates a solid research foundation in this field.

Table 1. Summary statistics of the articles collected

Description	Results
Timespan	2000:2025
Sources (Journals, Books, etc)	231
Documents	515
Annual Growth Rate %	6.65
Documents Average Age	4.23
Average citations per doc	31.05
References	25173
Keywords Plus (ID)	2953
Author's Keywords (DE)	1150
Authors	2031
Authors of Single-Authored Docs	7
Single-Authored Docs	10
Co-Authors per Doc	5.43
International Co-Authorships %	26.99

Source: Biblioshiny

The annual growth rate of 6.65% suggests a steady increase in scientific interest and output in probiotic encapsulation, which aligns with the rising awareness of probiotics' health benefits and their application in functional foods [43, 44]. The documents' average age of 4.23 years reveals that the field remains relatively contemporary, emphasizing the relevance and timeliness of ongoing research in this area. Furthermore, the average citations per document is 31.05, which points to a high impact and engagement within the scholarly community, reflecting the significance of probiotic encapsulation studies in food science and related disciplines.

A substantial volume of references, totaling 25,173, indicates extensive foundational literature, which researchers have drawn upon to advance the understanding of encapsulation technologies, such as microencapsulation and nanoencapsulation, in enhancing probiotic viability in various food matrices. The keywords, including Keywords Plus (ID) with 2,953 occurrences and Author's Keywords (DE) totaling 1,150.

There are 2,031 authors involved, with a minor portion of authors of single-authored documents, indicating a collaborative nature of research in this field. Only 10 documents are single-authored, reinforcing the need for multidisciplinary approaches and expertise in encapsulation, microbiology, and food technology. The co-authors per document average is 5.43, showcasing a strong collaborative trend, which is further supported by a notable International Co-authorships rate of 26.99%. This international collaboration is crucial for probiotic research, where knowledge sharing across countries and institutions contributes to innovative and region-specific encapsulation methods suitable for diverse dietary cultures [43].

In terms of document types, the majority consists of articles (407), followed by book chapters (15) and conference papers (16). The presence of conference papers suggests an ongoing discussion in the field, allowing researchers to share preliminary findings and gain feedback before formal journal publication. There is also a single erratum, letter, and short survey, which may indicate corrections, expert insights, and concise overviews, respectively.

3.1 Annual scientific production

Figure 2 depicts the annual growth in scientific publications on probiotic encapsulation for human food, based on data retrieved from Biblioshiny and the Scopus database. Covering the period from 2000 to 2024, it highlights the steady expansion of research activity in this field. Initially, from 2000 to 2010, the field saw minimal activity, with annual publications fluctuating between 0 to 5 articles. These numbers reflect the early stage of probiotic encapsulation research, as foundational methodologies and theories were being developed to explore its potential in food systems.

A gradual rise began in 2012, reaching 11 articles, and continued steadily until 2016, with 10–19 publications annually. A major growth spurt occurred after 2018, with publications increasing from 34 in 2019 to 69 in 2022, driven by advancements in encapsulation technologies. The most significant growth happened between 2023 and 2024, with articles jumping from 77 to 99, indicating stronger collaborations, innovations, and recognition of probiotics' importance in functional foods [33, 45, 46]. The field has grown rapidly, evolving from a niche area into a key domain in food science, addressing global health and nutrition challenges [47].

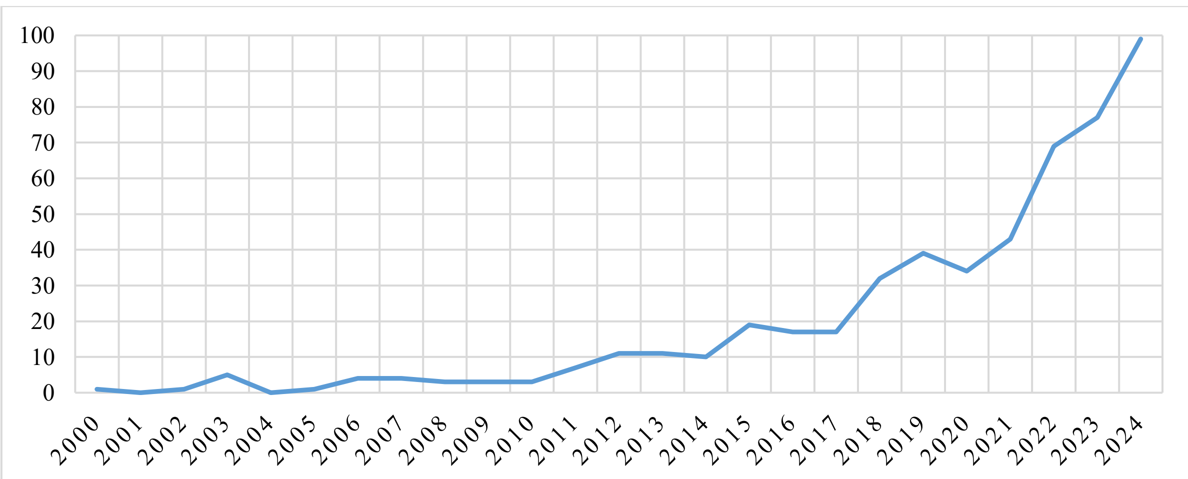


Figure 2. Annual trends in probiotic encapsulation research (2000–2024)
Source: Biblioshiny

Table 2. Top 10 most relevant journals on probiotic encapsulation research

Source	H_index	G_index	M_index	TC	NP	PY_start
LWT	17	29	0.85	1597	29	2006
Food Hydrocolloids	13	32	0.765	1182	32	2009
International Journal of Biological Macromolecules	9	18	0.818	357	19	2015
Food Research International	8	10	0.421	415	10	2007
Food Chemistry	7	10	0.389	649	10	2008
Journal of Food Processing and Preservation	7	11	0.778	185	11	2017
Journal of Food Science and Technology	7	8	0.636	280	8	2015
Carbohydrate Polymers	6	6	0.5	288	6	2014
Food Science and Nutrition	6	9	0.857	207	9	2019
Critical Reviews in Food Science and Nutrition	5	5	0.385	333	5	2013

3.2 The most relevant sources

The analysis of the most relevant sources for probiotic encapsulation research highlights their significant contributions, driven by their focused scopes, high-quality publications, and reputable publishers (Table 2). Among these, LWT - Food Science and Technology stands out as a leading source, with an H-index of 17, a G-index of 29, and 1,597 total citations (TC) from 29 published papers (NP) since its first publication in 2006. The H-index reflects its productivity and influence, as 17 of its articles have been cited at least 17 times, while the G-index emphasizes the cumulative impact of its most highly-cited work. Its M-index of 0.85, calculated by dividing the H-index by the years since its inception, demonstrates sustained contributions over time. LWT focuses on a broad range of food science and technology topics, including food safety, quality, and innovation, making it a key platform for publishing cutting-edge research on functional foods and encapsulation technologies. With an impact factor of 5.723 (2023), LWT has consistently provided a venue for innovative studies exploring the stability and viability of probiotics in diverse food matrices.

Similarly, Food Hydrocolloids has emerged as another critical journal in this field. Since 2009, it has accumulated an H-index of 13, a G-index of 32, and 1,182 total citations from 32 publications. The journal focuses on the physicochemical properties and applications of hydrocolloids, including their use as encapsulation matrices for probiotics. Its articles often explore how materials such as alginate, carrageenan, and chitosan improve probiotic delivery and stability during processing and storage. With an impact factor of 9.147 (2023), Food Hydrocolloids plays a pivotal role in advancing the technical understanding and practical applications of hydrocolloids, making it a top choice for researchers in the field of probiotic encapsulation.

Another noteworthy journal is the International Journal of Pharmaceutics, which has published 19 articles since 2015, accumulating an H-index of 9, a G-index of 18, and 357 total citations. Its M-index of 0.818 underscores its consistent annual contributions to the field. This journal is dedicated to pharmaceutical research, particularly drug delivery systems, formulation technologies, and controlled release mechanisms. Its impact factor of 6.321 (2023) reflects its influence in bridging pharmaceutical sciences and related fields, such as encapsulation of probiotics for therapeutic purposes. Researchers often turn to this journal for in-depth studies on encapsulation systems that enhance the viability and targeted delivery of probiotics in clinical and functional food applications.

Food Research International and Food Chemistry are also essential contributors to this research domain. With total citations of 415 and 649, respectively, these journals have consistently published work on integrating encapsulation technologies into food systems. Food Research International, which has an H-index of 8 and an M-index of 0.421, focuses on food safety, quality, and the application of novel technologies in the food industry. Similarly, Food Chemistry, with an H-index of 7 and an impact factor of 9.231 (2023), emphasizes the chemical and functional properties of food components, making it an excellent platform for research on the interaction between encapsulated probiotics and food matrices. These journals contribute to practical innovations, such as incorporating encapsulated probiotics into beverages, dairy products, and functional foods, thereby ensuring better consumer acceptance and product stability.

Carbohydrate Polymers and the Journal of Food Science also play crucial roles in advancing probiotic encapsulation research. Carbohydrate Polymers, with an H-index of 6 and a G-index of 6, focuses on the chemistry, physics, and biology of carbohydrate-based materials. Its articles often explore the use of natural polymers such as pectin and alginate for encapsulating probiotics, ensuring their survival during gastrointestinal transit. The journal's impact factor of 10.723 (2023) reflects its high-quality publications and relevance in material science and food applications. Meanwhile, the Journal of Food Science, with an H-index of 7 and an M-index of 0.636, highlights research on food safety, quality, and processing technologies. Despite its relatively lower total citations (280), the journal remains a valuable resource for applied research in food science, including studies on encapsulation.

Recent entrants, such as Food Science and Nutrition and Critical Reviews in Food Science and Nutrition, have also made notable contributions. Food Science and Nutrition, which began in 2019, has achieved a high M-index of 0.857, demonstrating rapid growth and influence in a short time. The journal focuses on various aspects of food science, nutrition, and functional food development, with an emphasis on consumer health and well-being. Critical Reviews in Food Science and Nutrition, on the other hand, is known for publishing comprehensive reviews on emerging topics, such as the use of encapsulation in functional foods. Its impact factor of 12.225 (2023) underscores its reputation as a leading source for reviews that synthesize and advance knowledge in the field.

Overall, these journals collectively shape the research landscape of probiotic encapsulation by offering platforms for high-quality, impactful publications. The H-index, G-index, and M-index metrics further highlight their consistent contributions and influence over time. Their diverse scopes—ranging from food science and hydrocolloids to pharmaceuticals and material science—enable interdisciplinary approaches, fostering innovation in probiotic encapsulation technologies. Combined with the strong reputations of their publishers, such as Elsevier and Taylor & Francis, these journals remain instrumental in driving advancements that address critical challenges in global health and nutrition through functional foods and therapeutic applications.

3.3 The most contributing authors

The analysis of the ten most relevant authors contributing to research on probiotic encapsulation for functional foods provides a detailed understanding of their productivity and impact in the field (Table 3). The data reveal that the number of articles authored by these researchers varies significantly, with a mean of 12.4 articles and a standard deviation of 5.93. This variation suggests that while some authors are highly prolific, contributing a substantial number of publications, others have made more modest contributions. The most productive authors, such as Afzaal M. and Saeed F., have authored 23 articles each, marking them as key contributors to the advancement of this research area.

Table 3. The most prolific authors

Authors	Articles	Articles Fractionalized
Afzaal M	23	2.48
Saeed F	23	2.48
Ateeq H	14	1.39
Ahmed A	11	1.23
Mcclements DJ	11	1.66
Ahmad A	10	1.00
Wang Y	9	1.19
Kailasapathy K	8	5.50
Shah YA	8	0.70
Asghar A	7	0.65

Source: Biblioshiny

When fractionalized contributions are considered—accounting for co-authorship—the range narrows, with values spanning from 0.65 to 5.5 and an average of 1.83. This adjustment provides a more nuanced view of each author's individual impact, reflecting their specific contributions to collaborative research efforts. The relatively lower mean and range in fractional contributions compared to raw article counts highlight the collaborative nature of this field, where multiple authors often work together on publications.

The interquartile range (IQR) for article contributions lies between 8.25 and 13.25 articles, indicating that the majority of authors have outputs within this range, while a few outliers, such as the most prolific contributors, extend well beyond it. Similarly, the IQR for fractionalized contributions is between 1.05 and 2.28, reflecting moderate contributions from most authors, with a smaller subset achieving higher fractionalized scores.

These findings underscore the existence of a core group of researchers driving advancements in probiotic encapsulation for functional foods. Their consistent and significant contributions to the literature play a pivotal role in shaping the research landscape of this field. This information is not only valuable for bibliometric evaluations but also serves as a guide for researchers seeking to identify leading experts and potential collaborators in probiotic encapsulation research.

The data reflect author productivity in the field of probiotic encapsulation research, analyzed through Lotka's Law (Table 4), which predicts that a small number of authors will produce the majority of the publications while most authors contribute minimally. Here, 79.7% of authors wrote only one document, demonstrating a high proportion of single-contribution authors. In contrast, authors producing multiple documents diminish exponentially, with only 13% contributing two documents, 4% contributing three, and so on. Notably, only one author has written ten documents.

This distribution highlights the collaborative and specialized nature of the field, where a small core of prolific authors drives the majority of the research output, consistent with Lotka's inverse square law. The findings emphasize the importance of identifying and engaging with these core contributors to understand and further the field's academic advancements.

Table 4. Lotka's Law distribution

Documents Written	No. of Authors	Proportion of Authors
1	1618	0.797
2	262	0.129
3	82	0.04
4	28	0.014
5	17	0.008
6	11	0.005
7	4	0.002
8	2	0.001
9	1	0
10	1	0

Source: Biblioshiny

3.4 Affiliations

The data presents the ten most relevant academic affiliations contributing to research in probiotic encapsulation for functional foods (Table 5), highlighting their productivity based on the number of articles published. The leading institution, Government College University Faisalabad, has contributed 86 articles, significantly surpassing the second-ranked Northwest A&F University with 55 articles. This indicates the prominent role of Government College University Faisalabad in advancing this field, likely due to dedicated research groups or collaborations focused on functional food innovations.

Table 5. The most relevant affiliations

Affiliation	Articles
Government College University Faisalabad	86
Northwest A&f University	55
Northeast Agricultural University	47
Government College University	46
Islamic Azad University	41
Jiangnan University	32
South China University of Technology	32
Zhejiang University	29
University Of Belgrade	28
Huazhong Agricultural University	25

Source: Biblioshiny

Other key contributors include Northeast Agricultural University (47 articles) and Islamic Azad University (41 articles), both emphasizing their strong focus on agricultural and food sciences. The presence of Jiangnan University and South China University of Technology, each with 32 articles, underscores China's active participation in this research domain, supported by their expertise in food technology and processing. Zhejiang University (29 articles) and Huazhong Agricultural University (25 articles) further emphasize China's dominance in this field.

International contributors like the University of Belgrade (28 articles) demonstrate the global nature of this research, reflecting collaborative efforts and the universal relevance of probiotics in health and food applications. These affiliations collectively highlight a concentrated effort from institutions with strong agricultural, biological, and food science research backgrounds, suggesting significant academic and industrial interest in advancing probiotic encapsulation technologies. This distribution of contributions can guide researchers in identifying leading institutions for potential collaborations or accessing cutting-edge studies in the field.

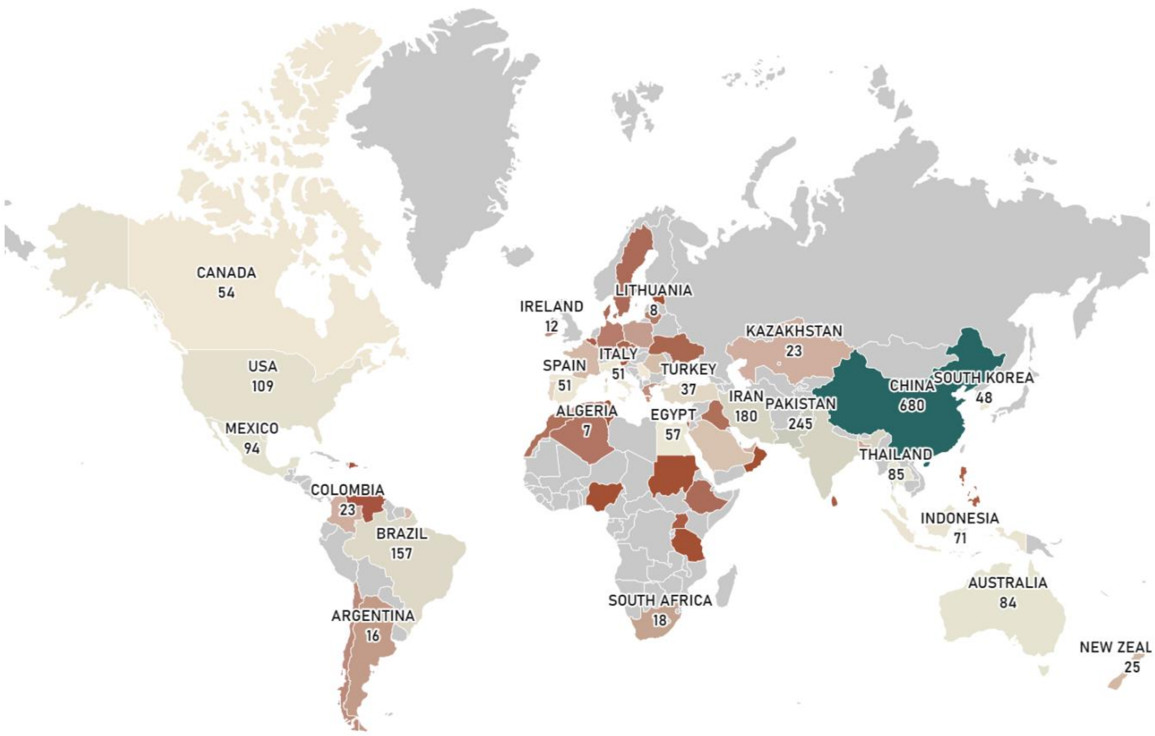


Figure 3. Global distribution of scientific production in probiotic encapsulation research (Scimago Graphica)

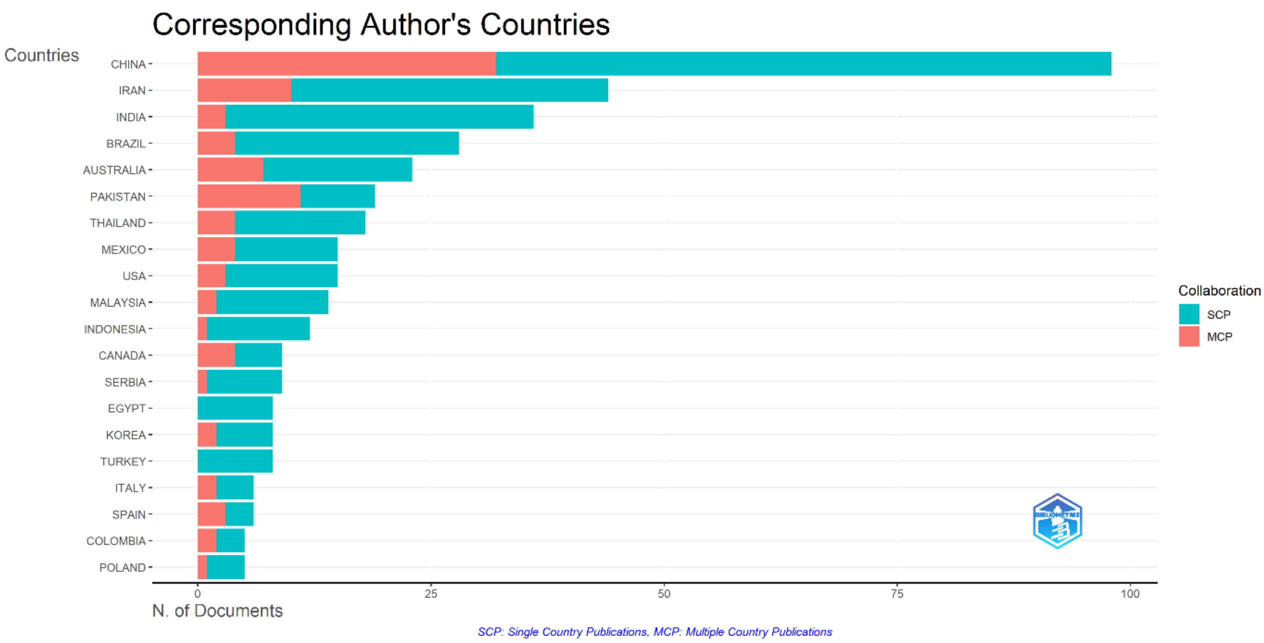


Figure 4. Corresponding authors' countries and their collaborative patterns in probiotic encapsulation research
Source: Biblioshiny

3.5 The most productive countries

Figure 3 highlights the most relevant countries contributing to probiotic encapsulation research. China emerges as the most prolific contributor, with 680 publications, underscoring its leadership in probiotic encapsulation research. This dominance can be attributed to several key factors. First, strong government support through targeted policies and funding initiatives has significantly advanced China's biotechnology and food science sectors. The government's emphasis on innovation and technological development in the life sciences, particularly through initiatives such as the "Made in China 2025" plan, has propelled research in fields like probiotic encapsulation. Industry demand for probiotic-enriched functional foods, driven by China's large population and growing interest in health and wellness, further stimulates research efforts. Active academic and industrial collaborations also play a crucial role, with universities and research institutions working closely with private companies to develop and commercialize encapsulation technologies. For example, the National Natural Science Foundation of China (NSFC) has provided substantial funding to biotechnology research, facilitating advancements in the encapsulation and delivery systems of probiotics.

Other leading countries in Asia include Pakistan (245 publications), Iran (180), and India (85). These countries have made significant strides in the field, benefiting from regional collaborations and increasing recognition of the importance of probiotics in functional foods. In Pakistan, the Higher Education Commission (HEC) has supported research in biotechnology through funding initiatives like the Indigenous PhD Fellowship Program, which encourages research on food biotechnology and nutraceuticals, including probiotics. Additionally, research institutions like the University of Agriculture Faisalabad have focused on the development of probiotic-based functional foods, receiving government support for collaborative projects with the private sector.

Iran's growing academic focus on biotechnology and nutrition, combined with policy support for scientific innovation, has bolstered its research output in probiotic encapsulation. The Iran National Science Foundation (INSF) funds projects related to food science and biotechnology, which include research on probiotic encapsulation to enhance functional foods. The Tehran University of Medical Sciences has been at the forefront, partnering with the food industry to develop probiotic-based products.

Similarly, India's burgeoning food and health industry, along with government-funded programs aimed at improving public health, has encouraged research in probiotics as part of its larger focus on functional foods and nutraceuticals. The Indian Council of Medical Research (ICMR) and the Department of Biotechnology (DBT) have launched various initiatives to support functional food research, including probiotics. One such initiative is the Biotechnology Industry Research Assistance Council (BIRAC), which has provided funding to research institutions and startups focusing on the development of probiotic delivery systems (Patel et al., 2019). Additionally, academic institutions like the Indian Institute of Technology (IIT) Delhi are collaborating with the food industry to develop encapsulation technologies to improve probiotic stability and bioavailability.

The bar chart illustrates the distribution of publications by corresponding authors' countries in probiotic encapsulation research, highlighting both Single Country Publications (SCP) and Multiple Country Publications (MCP). The blue segments indicate SCP, representing domestic collaborations. The red segments indicate MCP, representing international collaborations (Figure 4). China dominates the field with the highest number of publications, primarily through SCP, indicating strong domestic research activity and infrastructure. Iran, India, and Brazil follow, showcasing significant contributions with a mix of SCP and MCP, reflecting growing regional and international collaborations in these countries.

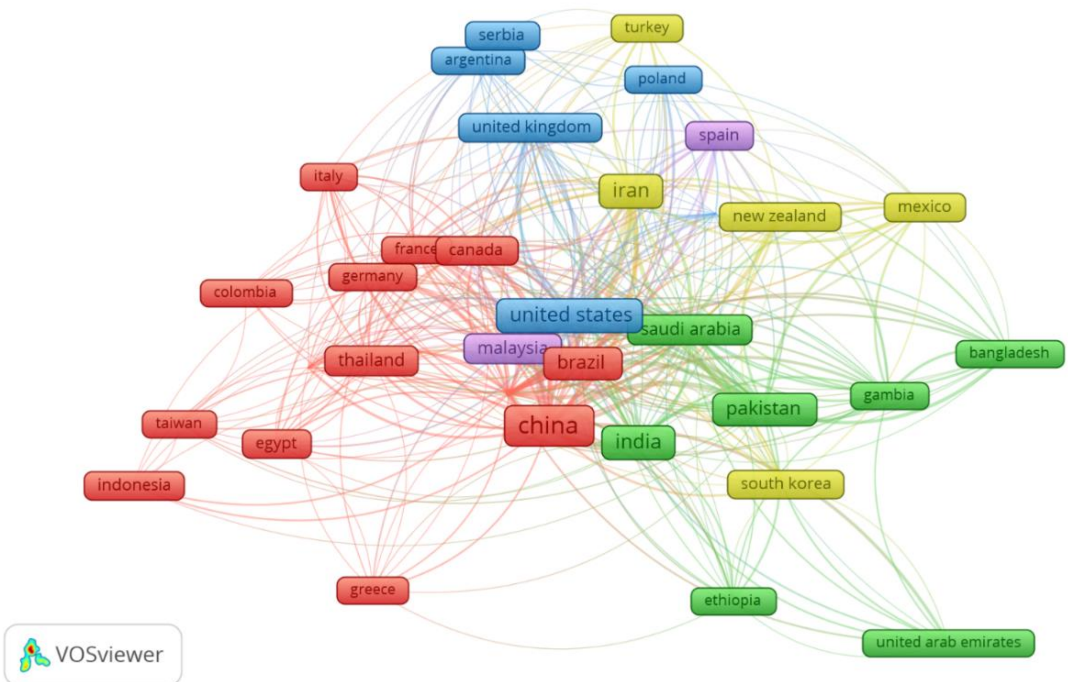


Figure 5. Global collaboration network in probiotic encapsulation research

The network visualization depicts global collaborations between countries in probiotic encapsulation research. Each node represents a country, with the size of the node corresponding to the number of publications. The lines indicate collaboration links, with thicker lines representing stronger collaboration intensity. Colors indicate clusters of closely collaborating countries.

Source: Biblioshiny

Australia and Pakistan also exhibit a balanced approach, with a notable presence of MCP, suggesting active participation in international partnerships. Countries such as Thailand, Mexico, and the USA have moderate output, with a substantial fraction of their work involving international collaborations, as indicated by the higher MCP proportions. Further down the list, nations like Malaysia, Indonesia, Canada, and Serbia contribute to the field through a mix of SCP and MCP, emphasizing both domestic research efforts and collaborative endeavors. European countries, including Italy, Spain, and Poland, show smaller outputs, predominantly SCP, reflecting niche but focused contributions. This distribution indicates the field's global reach, with leading contributions from Asia, particularly China, and notable collaborations emerging among developed and developing nations. It underscores the importance of fostering international partnerships to advance research in probiotic encapsulation technologies.

The visualization presented represents the network analysis of citation relationships among countries in the research field of probiotic encapsulation (Figure 5). Generated using VOSviewer, this map highlights the interconnectedness of countries based on shared citations, with clusters identified through color coding. The threshold applied in the analysis was a minimum of 5 documents per country, and out of 70 countries, 34 met this criterion. Each node represents a country, and the size of the node reflects the number of documents or citations associated with that country. The lines between nodes indicate citation links, and the thickness of these lines represents the strength of these connections.

The map is divided into multiple clusters, with each cluster represented by a unique color. These clusters reflect groups of countries that are closely linked based on citation relationships, indicating collaborative or influential research activities within and between these groups.

1) Red Cluster: Western Collaborations and Asian Contributions The red cluster includes countries such as China, Germany, Thailand, Canada, France, Indonesia, and Egypt. This cluster likely represents a mix of European and Asian countries with significant contributions to probiotic encapsulation research. China, being one of the largest nodes in this cluster, plays a central role in driving research and collaborations. The strong connections between China and other countries in this cluster highlight its influence in both producing and citing research globally. The inclusion of Thailand and Indonesia reflects the growing prominence of Southeast Asia in probiotic research, particularly in developing functional foods with regional applications.
2) Green Cluster: South and Southeast Asian Focus The green cluster comprises countries such as India, Pakistan, Bangladesh, Saudi Arabia, and Ethiopia. This cluster reflects the regional research emphasis on probiotics and encapsulation, with India being a key contributor. The strong links among these countries indicate collaborations within the region, possibly driven by shared dietary practices and the growing demand for functional foods. The focus of this cluster likely revolves around affordable probiotic solutions and encapsulation technologies tailored for developing nations.
3) Blue Cluster: North American and European Collaborations The blue cluster includes countries like the United States, the United Kingdom, Serbia, and Argentina. The United States, a significant node in this cluster, is one of the leading contributors to probiotic research globally. Its strong connections with the United Kingdom and European countries reflect transatlantic collaborations, particularly in advanced encapsulation technologies and clinical applications of probiotics. The inclusion of Serbia and Argentina indicates a broader international scope, suggesting these countries are key contributors in niche areas or emerging markets.
4) Yellow Cluster: Emerging Collaborators The yellow cluster features countries such as Iran, Turkey, Mexico, New Zealand, and Poland. This cluster highlights emerging players in probiotic encapsulation research, with Iran and Turkey taking prominent positions. These countries are increasingly contributing to the field, focusing on specific applications of encapsulation technologies. The connections in this cluster suggest growing collaborations between these nations and more established research hubs in Europe and Asia.
5) Purple Cluster: Southeast Asia and Global Outreach. The purple cluster includes Brazil, Malaysia, and Spain, highlighting collaborative efforts between Southeast Asia, Europe, and Latin America. Brazil serves as a central node in this cluster, reflecting its dual role as a producer of probiotic research and a collaborator with European countries. Malaysia's presence in this cluster underscores Southeast Asia’s expanding role in probiotic research, particularly in functional food applications.

This visualization demonstrates the global nature of probiotic encapsulation research, with strong contributions and collaborations from countries across Asia, Europe, and the Americas. The clusters represent geographic and thematic groupings, showing that countries with similar research focuses tend to cite and collaborate with each other. Larger nodes like the United States, China, India, and Brazil indicate countries with a substantial number of documents and citations, reflecting their leadership in the field. Meanwhile, smaller nodes represent emerging players, highlighting the growing diversification of research contributions globally.

3.6 The most cited papers globally and locally

The ten most globally cited documents in the field of probiotic encapsulation have significantly contributed to advancing research and practical applications in this area (Table 6). The most cited work, authored by Whorwell et al. [48] in the *American Journal of Gastroenterology*, with 692 citations, has likely provided critical insights into the role of probiotics in gastrointestinal health, laying a clinical foundation for encapsulation technologies aimed at delivering viable probiotics to target areas in the gut. Similarly, the article by Burgain et al. [49] in *Journal of Food Engineering* (680 citations) has likely addressed advancements in encapsulation techniques, focusing on improving the stability and efficiency of probiotic delivery systems in functional foods. Kailasapathy's [50] study in *Current Issues in Intestinal Microbiology* (398 citations) likely explores how encapsulated probiotics can better survive the gastrointestinal environment, emphasizing their role in modulating intestinal microbiota and improving health outcomes.

Table 6. The top 10 globally most-cited papers in the field of probiotic encapsulation

Title	Authors	Journal	TC	TCpY	N-TC
Efficacy of an encapsulated probiotic *Bifidobacterium infantis* 35624 in women with irritable bowel syndrome	[48]	American Journal of Gastroenterology	692	36.42	2.18
Encapsulation of probiotic living cells: From laboratory scale to industrial applications	[49]	Journal of Food Engineering	680	48.57	5.19
Microencapsulation of probiotic bacteria: Technology and potential applications	[50]	Current Issues in Intestinal Microbiology	398	17.30	1.00
Microencapsulation of bacteria: A review of different technologies and their impact on the probiotic effects	[51]	Innovative Food Science & Emerging Technologies	374	37.40	7.37
Survival of free and encapsulated probiotic bacteria and their effect on the sensory properties of yoghurt	[52]	LWT - Food Science and Technology	372	19.58	1.17
Effect of microencapsulation and resistant starch on the probiotic survival and sensory properties of synbiotic ice cream	[53]	Food Chemistry	339	19.94	2.16
Microencapsulation of microbial cells	[54]	Journal of Food Engineering	274	22.83	3.22
Electrospinning as a useful technique for the encapsulation of living bifidobacteria in food hydrocolloids	[46]	Food Hydrocolloids	219	16.85	3.36
Microencapsulation of probiotic cells by means of rennet-gelation of milk proteins	[55]	Food Hydrocolloids	197	12.31	1.12
Probiotic bacteria: Selective enumeration and survival in dairy foods	[56]	Journal of Dairy Science	194	7.76	1.00

Source: Biblioshiny
TC: Total citations, TCpY: Total citations per year, N-TC: Normalized total citations.

Study [51] published in *Innovative Food Science and Emerging Technologies* (374 citations) probably highlights innovative approaches to encapsulation, introducing advanced materials or methods, such as nanotechnology, to enhance probiotic functionality in food systems. Kailasapathy's second highly cited work [52] from 2006 in *LWT – Food Science and Technology* (372 citations) addresses the technological challenges of incorporating probiotics into functional food matrices, likely offering solutions for large-scale applications. Meanwhile, study [53] in *Food Chemistry* (339 citations) contributes by examining the chemical interactions between probiotics and encapsulating materials, focusing on enhancing stability and bioavailability.

Study [54] in the *Journal of Food Engineering* (274 citations) likely discusses industrial-scale advancements in probiotic encapsulation, contributing to the scalability of functional food production. Studies [46, 55], both published in *Food Hydrocolloids* (219 and 197 citations, respectively), focus on hydrocolloids as effective encapsulating materials, exploring their properties in improving probiotic protection during processing and storage. Lastly, Shah [56]'s article in *Journal of Dairy Science* (194 citations) likely provided early insights into the integration of probiotics in dairy products, paving the way for their inclusion in widely consumed functional foods.

These studies collectively address key challenges in probiotic encapsulation, including enhancing stability, improving viability, exploring innovative materials and methods, and integrating probiotics into diverse food matrices. They have not only advanced the scientific understanding of encapsulation technologies but have also laid the groundwork for their practical application in developing effective and accessible functional foods. Their widespread citations reflect their foundational impact on shaping this dynamic research field.

The ten most locally cited documents in the field of probiotic encapsulation represent foundational studies that have shaped local research directions and significantly contributed to advancing the field within specific academic or regional contexts (Table 7). These studies address critical aspects of probiotic encapsulation, such as stability, viability, material selection, and innovative encapsulation methods.

Study [49], *Journal of Food Engineering*, with the highest local citations (58), likely focuses on advanced encapsulation techniques to improve the stability and delivery of probiotics in functional foods. This work has likely guided regional research on developing scalable methods to enhance probiotic viability during food processing. Study [52], *LWT* (36 local citations), and Study [50], *Current Issues in Intestinal Microbiology* (31 local citations), provide a comprehensive understanding of the survival mechanisms of encapsulated probiotics in gastrointestinal conditions and highlight technological challenges in incorporating probiotics into food systems. These studies have influenced local research in refining encapsulation methods for practical applications.

Studies [57, 58], *LWT - Food Science and Technology* (30 and 25 local citations), and study [53], *Food Chemistry* (26 local citations), focus on novel encapsulating materials and their interactions with probiotics, emphasizing improved stability and bioavailability. These studies contribute to selecting materials that optimize probiotic functionality, especially in diverse food matrices. Study [59] (22 local citations) likely explores encapsulation strategies tailored for specific food products, enhancing their sensory and functional attributes while maintaining probiotic viability. Recent studies, such as study [47], *Trends in Food Science and Technology* (22 local citations), reflect the integration of cutting-edge technologies like nanotechnology into probiotic encapsulation, paving the way for more precise and effective delivery systems. Study [55], *Food Hydrocolloids* (22 local citations), and study [59], *Pharmaceutics* (22 local citations), delve into the mechanisms and benefits of using hydrocolloids and pharmaceutical approaches for encapsulating probiotics, offering valuable insights into industrial and clinical applications. Lastly, Study [60], *Hayati Journal of Biosciences* (21 local citations), likely addresses the incorporation of probiotics into functional dairy products, emphasizing sensory improvement and consumer acceptance.

Table 7. The top 10 locally most-cited papers in the field of probiotic encapsulation

Title	Authors	Journals	LC	GC	LC/GC Ratio (%)	NLC	NGC
Encapsulation of probiotic living cells: From laboratory scale to industrial applications	[49]	Journal of Food Engineering	58	680	8.53	5.41	5.19
Survival of free and encapsulated probiotic bacteria and their effect on the sensory properties of yoghurt	[52]	LWT - Food Science and Technology	36	372	9.68	2.03	1.17
Microencapsulation of probiotic bacteria: technology and potential applications	[50]	Current issues in Intestinal Microbiology	31	398	7.79	1.00	1.00
Survival of probiotics encapsulated in chitosan-coated alginate beads in yoghurt from UHT- and conventionally treated milk during storage	[57]	LWT - Food Science and Technology	30	190	15.79	1.69	0.60
Effect of microencapsulation and resistant starch on the probiotic survival and sensory properties of synbiotic ice cream	[53]	Food Chemistry	26	339	7.67	1.95	2.16
Effect of chitosan-alginate encapsulation with inulin on survival of *Lactobacillus rhamnosus GG* during apple juice storage and under simulated gastrointestinal conditions	[58]	LWT - Food Science and Technology	25	164	15.24	6.16	3.37
Encapsulation of probiotics and nutraceuticals: Applications in functional food industry	[47]	Trends in Food Science & Technology	22	171	12.87	11.97	5.96
Microencapsulation of probiotic cells by means of rennet-gelation of milk proteins	[55]	Food Hydrocolloids	22	197	11.17	1.78	1.12
Probiotic encapsulation technology: From microencapsulation to release into the gut	[59]	Pharmaceutics	22	174	12.64	4.10	2.67
Microencapsulation improved probiotics survival during gastric transit	[60]	HAYATI Journal of Biosciences	21	169	12.43	5.58	4.54

Source: Biblioshiny
LC: Local citation, GC: Global citation, NLC: Normalized local citation, NGC: Normalized global citation.

Collectively, these studies represent a critical body of work driving local advancements in probiotic encapsulation research. They address the specific challenges and opportunities within regional food industries and academic communities, contributing significantly to the development and optimization of functional food products. Their influence extends to shaping methodologies, material choices, and application strategies, ensuring that probiotics deliver maximum health benefits to consumers.

In addition, Figure 6 represents the Reference Publication Year Spectroscopy (RPYS), highlighting the distribution of cited references over time in spectroscopy research. During the early years (1870–1970), cited references are minimal, reflecting the foundational phase of spectroscopy with occasional breakthroughs laying the groundwork for future advancements. From the 1970s to the 1990s, there was a gradual increase in citations, coinciding with technological advancements in spectrometers and the expansion of spectroscopy applications in various fields. The exponential growth observed between 1990 and 2010 marks a period of widespread adoption and innovation, driven by the integration of laser-based spectroscopy and Fourier transform techniques.

Citations peak around the early 2010s, reflecting a culmination of intense research activity and significant contributions to the field. However, a slight decline after 2020 could indicate a shift toward newer techniques or interdisciplinary approaches that rely less on traditional spectroscopy studies, along with a natural lag in citing recent works. The red line, representing deviations from the median, shows notable peaks corresponding to years of milestone publications or paradigm-shifting discoveries, emphasizing the sporadic nature of transformative research in the field. This RPYS analysis illustrates the historical evolution of spectroscopy, highlighting key periods of innovation and providing insights into the scientific progress and foundational works that have shaped the discipline.

3.7 Thematic evolution

The thematic evolution of research on probiotics and encapsulation illustrates how this field has expanded and specialized over time, reflecting a shift from foundational studies to advanced applications and emerging technologies (Figure 6). Between 2000 and 2018, research primarily focused on understanding the basic properties and health benefits of probiotics, with themes centered around *Lactobacillus plantarum*, *Lactobacillus acidophilus*, and general probiotic bacteria. During this phase, the concept of probiotic encapsulation emerged as a foundational area, exploring technologies to improve the stability and viability of probiotics during processing and storage.

From 2019 to 2021, the focus diversified, with increased attention on broader applications of probiotics, such as their interaction with gut microbiota and prebiotics like inulin. This period saw significant progress in developing encapsulation systems to enhance probiotic viability and bioaccessibility, particularly in targeted delivery to the gastrointestinal tract. Themes like immunity and colon-specific delivery emerged, highlighting the field's growing emphasis on therapeutic applications of probiotics. Additionally, the use of natural polymers and materials for encapsulation gained traction, further advancing synbiotic systems that combine probiotics with prebiotics. In the period of 2022 to 2023, the research became more specialized, with a focus on technological advancements in encapsulation techniques, including microencapsulation, spray drying, and hydrogel systems. These innovations aimed to optimize the delivery and release of probiotics in the digestive system while ensuring their protection against harsh gastrointestinal conditions. Researchers began integrating probiotics into functional foods and exploring polysaccharides and sodium alginate as encapsulating materials. The development of in vitro digestion models also became prominent, allowing for better simulation and study of probiotic behavior and functionality under digestive conditions.

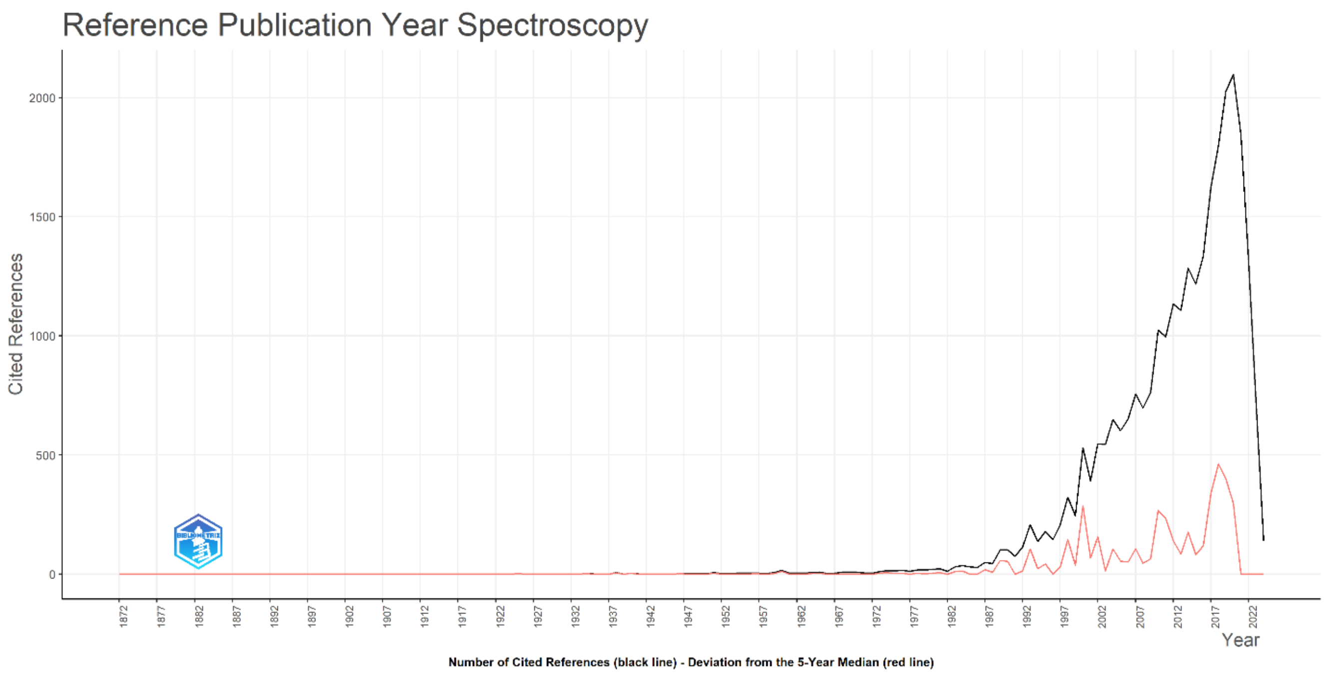


Figure 6. Reference publication year spectroscopy (RPYS)
The black line shows the total number of cited references by year, while the red line indicates deviations from the five-year median, pinpointing periods of significant contributions.
Source: Biblioshiny

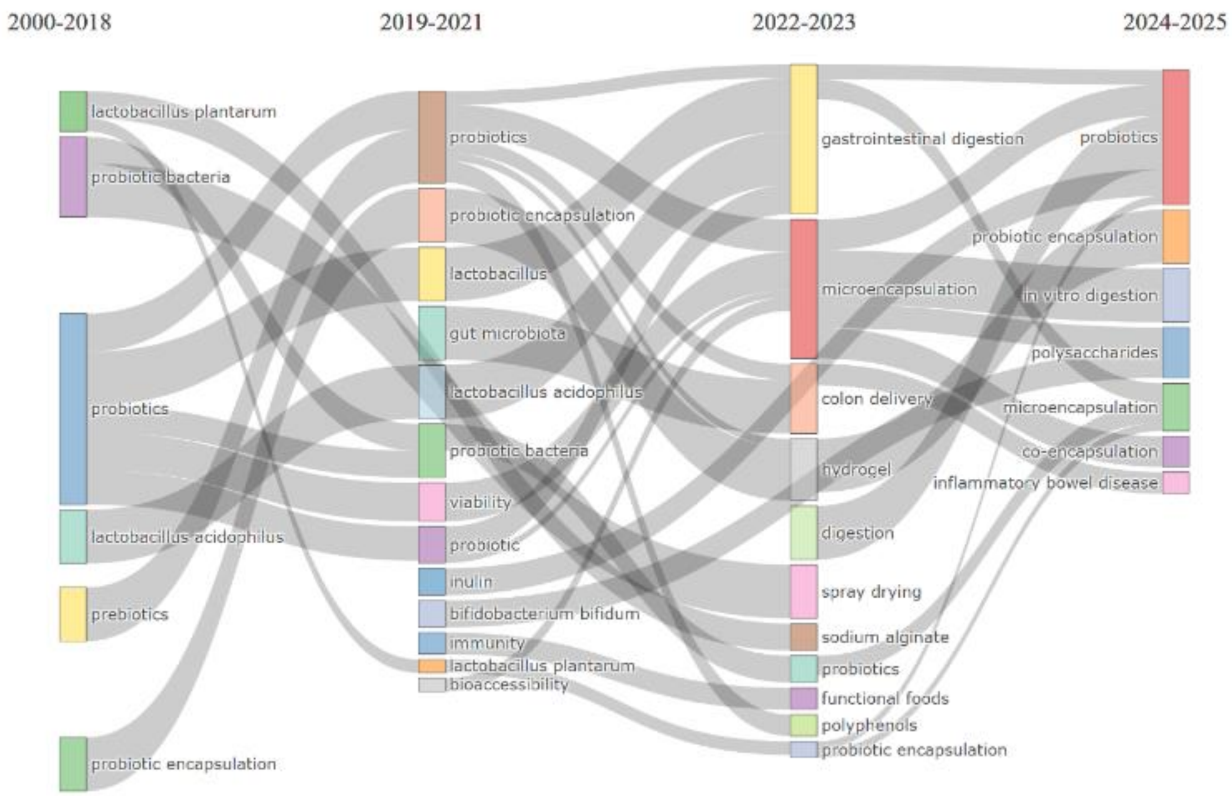
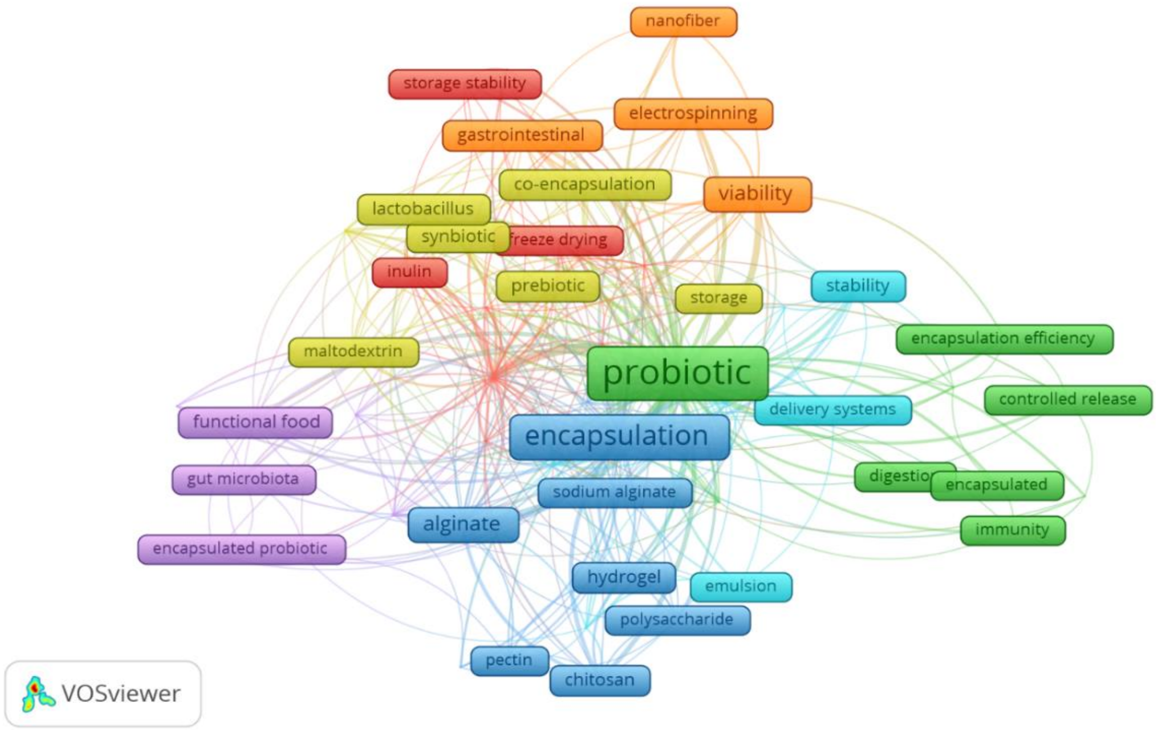
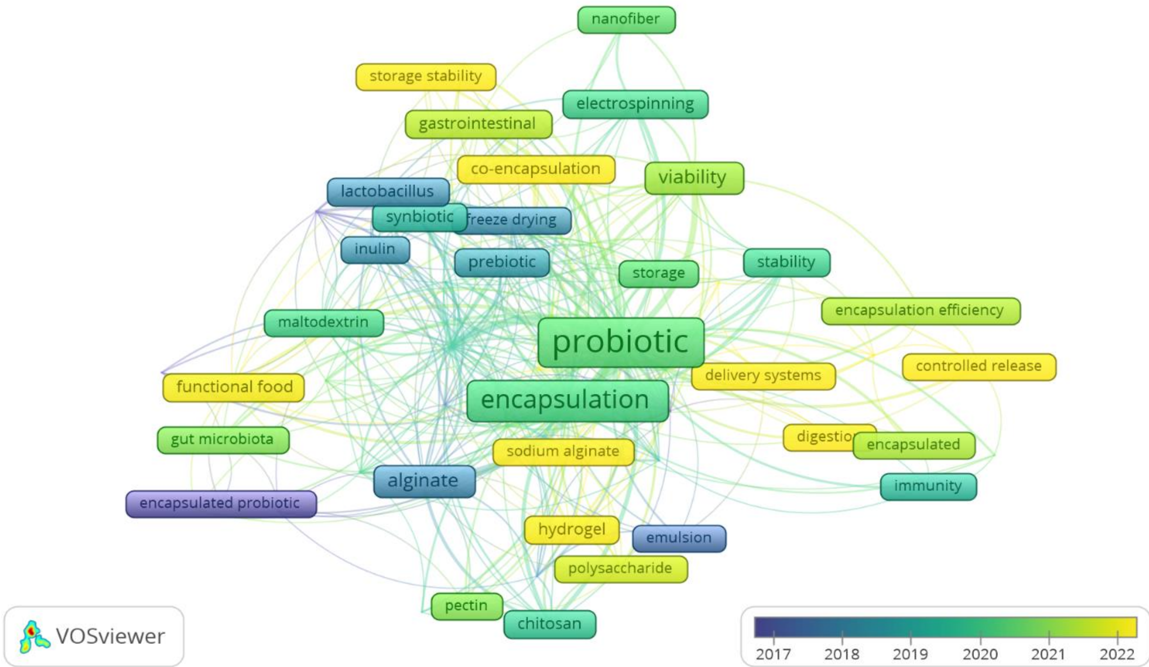


Figure 7. Thematic evolution
Source: Biblioshiny



(A)



(B)

Figure 8. (A) Network visualization; (B) Overlay visualization
Source: Vosviewer

Looking ahead to 2024 and 2025, emerging themes suggest a shift toward even more advanced and targeted applications. Co-encapsulation of probiotics with other bioactive compounds, such as polyphenols, is expected to enhance their therapeutic potential for conditions like inflammatory bowel disease. Advanced hydrogel systems and microencapsulation techniques are poised to improve the precision and efficacy of probiotic delivery to specific sites in the gastrointestinal tract. Additionally, in vitro digestion models will continue to evolve, providing deeper insights into the bioavailability and functionality of probiotics. Overall, the future of this field lies in leveraging cutting-edge technologies, such as nanotechnology and personalized nutrition, to integrate probiotics into multifunctional delivery systems aimed at improving gut health and addressing complex health challenges. This evolution highlights the growing significance of probiotics as key components in functional foods and therapeutic interventions.

The network and overlay visualizations of probiotic encapsulation research provide an intricate depiction of the thematic structure and its evolution over time (Figure 7). These visualizations highlight the interconnectedness of keywords, their co-occurrence, and the chronological emergence of research themes, offering critical insights into the progression and future directions of this dynamic field.

The network visualization (Figure 8(A)) showcases clusters of related keywords, each representing distinct thematic areas within probiotic encapsulation research. Larger nodes, such as "probiotic," "encapsulation," and "delivery systems," dominate the visualization, reflecting their central role in the research landscape. The green cluster is at the core of this network and includes essential topics such as probiotic viability, encapsulation efficiency, stability, and controlled release. This cluster emphasizes the primary objective of encapsulation research, ensuring probiotics survive harsh environmental conditions during processing, storage, and gastrointestinal transit while maintaining their efficacy. The strong interconnections within this cluster reflect the synergy between encapsulation techniques and their optimization for delivering probiotics effectively to target sites in the gut.

The blue cluster highlights the materials and methods employed in encapsulation systems. Keywords such as "alginate," "sodium alginate," "hydrogel," "pectin," and "chitosan" dominate this cluster, reflecting the extensive research into both natural and synthetic materials for encapsulation. These materials are critical for improving probiotic stability, protecting against environmental stressors, and enabling controlled release mechanisms. The inclusion of keywords like "emulsion" and "polysaccharide" suggests a focus on innovative material combinations and encapsulation strategies to enhance the effectiveness of delivery systems.

The yellow cluster focuses on the broader applications of encapsulated probiotics, particularly in the context of functional foods and gut health. Keywords such as "functional food," "gut microbiota," "synbiotic," and "inulin" represent the integration of probiotics into food matrices designed to deliver health benefits beyond basic nutrition. This cluster also includes preservation techniques like "freeze drying" and additives like "maltodextrin," indicating a focus on maintaining the viability of probiotics during storage and their compatibility with various food systems.

The orange cluster showcases the emergence of advanced encapsulation technologies and precision delivery systems. Keywords such as "nanofiber," "electrospinning," "co-encapsulation," and "gastrointestinal" highlight the field's increasing adoption of cutting-edge techniques like nanotechnology to improve encapsulation efficiency and targeted delivery. These methods aim to address specific health conditions, such as gastrointestinal disorders, by ensuring precise release and enhanced functionality of probiotics.

The overlay visualization adds a temporal dimension to these themes, illustrating the evolution of the field over time (Figure 8(B)). Keywords are color-coded based on their average publication year, with older topics shown in blue, intermediate topics in green, and the most recent trends in yellow. Early research, represented by keywords like "alginate," "pectin," "functional food," and "probiotic," focused on foundational aspects of probiotic encapsulation, such as identifying suitable materials and ensuring stability. These foundational studies established the groundwork for subsequent advancements in encapsulation science.

As the field matured, intermediate themes gained prominence around 2019–2020, as reflected by keywords like "delivery systems," "viability," "controlled release," and "encapsulation efficiency." These topics signify a period of refinement in encapsulation techniques, with a focus on optimizing systems for specific applications, improving bioavailability, and ensuring the efficacy of probiotics in functional food products.

Recent research trends, highlighted in yellow, emphasize cutting-edge technologies and applications. Terms such as "nanofiber," "electrospinning," "co-encapsulation," and "gastrointestinal" demonstrate the field’s shift toward high-precision delivery systems and advanced encapsulation methods. These keywords represent the adoption of nanotechnology and co-encapsulation strategies to address emerging challenges, such as combining probiotics with other bioactive compounds for synergistic effects and targeting specific health outcomes, like modulating gut microbiota or treating chronic gastrointestinal disorders.

The progression from blue to yellow in the overlay visualization illustrates the thematic evolution of the field, transitioning from basic research on materials and encapsulation methods to advanced applications involving innovative technologies. This evolution reflects the dynamic nature of probiotic encapsulation research, driven by growing consumer demand for functional foods, increasing interest in personalized nutrition, and the need to address global health challenges.

Overall, these visualizations provide a comprehensive overview of the probiotic encapsulation research landscape, showcasing its thematic richness, temporal progression, and future potential. The field has progressed from exploring basic encapsulation materials and methods to developing sophisticated delivery systems that integrate cutting-edge technologies like nanofibers and electrospinning. As the research continues to evolve, it is poised to address critical health challenges, enhance the functionality of probiotics, and advance the development of next-generation functional foods, paving the way for innovative solutions in global health and nutrition.

3.8 Shifting paradigms in probiotic encapsulation

The field of probiotic encapsulation has witnessed a transformative journey, evolving from fundamental studies aimed at ensuring probiotic viability to advanced multifunctional delivery systems tailored to address specific health challenges. This shift reflects both the growing scientific understanding of probiotics and their interactions with the human body and the increasing consumer demand for functional foods with proven health benefits.

3.8.1 Early research: Establishing the basics of probiotic encapsulation

Initially, research in probiotic encapsulation focused on addressing the inherent challenges of maintaining probiotic viability during processing, storage, and gastrointestinal transit. Probiotics, such as *Lactobacillus acidophilus* and *Bifidobacterium longum*, are highly sensitive to environmental stressors like heat, moisture, oxygen, and acidic conditions. Early encapsulation methods employed materials like alginate, gelatin, and carrageenan, which provided basic protection against harsh conditions. These studies established the foundational understanding of encapsulation as a tool for enhancing probiotic stability and ensuring effective delivery to the gut. A seminal work [52] highlighted the role of encapsulation in improving the survival of probiotics through the acidic environment of the stomach, laying the groundwork for future advancements in delivery technologies.

3.8.2 Mid-phase development: Technological innovations and functional integration

As the field matured, the focus shifted toward improving the efficiency, scalability, and functionality of encapsulation systems. This phase saw the development of advanced technologies like microencapsulation, spray drying, and emulsion-based encapsulation. For example, the work of Burgain et al. [49] in the *Journal of Food Engineering* demonstrated how microencapsulation using alginate and chitosan could significantly enhance the stability of probiotics under simulated gastrointestinal conditions. These advancements not only improved the protective capabilities of encapsulation materials but also opened new avenues for incorporating probiotics into functional foods.

The integration of probiotics into diverse food systems became a key theme during this period, driven by the rising demand for functional foods. Studies explored the incorporation of encapsulated probiotics into dairy products, beverages, and even baked goods. Functional food formulations aimed to deliver probiotics in a convenient and palatable manner, aligning with consumer preferences. Thematic analyses, such as those conducted by Homayouni et al. [53], highlighted the compatibility of encapsulated probiotics with food matrices and their potential to enhance product functionality without compromising sensory attributes.

3.8.3 Recent advancements: multifunctionality and precision delivery

In recent years, probiotic encapsulation has undergone a paradigm shift toward multifunctional and precision delivery systems. This phase has been marked by the emergence of co-encapsulation technologies, where probiotics are combined with other bioactive compounds, such as prebiotics, polyphenols, and omega-3 fatty acids. Co-encapsulation aims to create synergistic effects, enhancing the therapeutic potential of probiotics for specific health conditions. For instance, studies like those by Gandomi et al. [58] explored the encapsulation of probiotics with inulin, demonstrating improved gut microbiota modulation and targeted colon delivery.

Another significant advancement has been the adoption of hydrogel-based systems and nanotechnology for encapsulation. Hydrogels, derived from natural polymers like sodium alginate and carrageenan, provide superior protection against harsh gastric conditions while enabling controlled release in the intestines. Nanostructured delivery systems further enhance bioavailability and precision, paving the way for personalized nutrition strategies. The work of López-Rubio et al. [46] in *Food Hydrocolloids* exemplifies this trend, highlighting the use of hydrocolloids to create dynamic and responsive encapsulation systems.

3.8.4 Emerging themes and future directions

Thematic evolution analyses conducted using tools like Biblioshiny and VOSviewer reveal emerging themes such as gut-brain axis modulation, psychobiotics, and metabolic health. These themes reflect the broadening scope of probiotic applications, moving beyond gut health to address conditions like anxiety, depression, and obesity. The use of in vitro digestion models, as discussed in recent studies (e.g., study [48]), has refined our understanding of how encapsulated probiotics interact with the digestive system, enabling the optimization of delivery systems for specific health outcomes.

Future directions in probiotic encapsulation research are likely to focus on personalized probiotics tailored to individual microbiomes. Advances in bioinformatics and molecular biology will play a pivotal role in identifying optimal strains and delivery methods for targeted health benefits. Additionally, the scalability and cost-effectiveness of advanced encapsulation technologies will remain critical challenges to address, particularly for their widespread adoption in the functional food industry.

4. CONCLUSIONS

4.1 Conclusions

The field of probiotic encapsulation has undergone substantial growth, evolving from foundational research aimed at improving probiotic survival to sophisticated multifunctional delivery systems designed to address specific health concerns. This bibliometric analysis, encompassing 515 articles, sheds light on the most prolific authors, leading institutions, contributing countries, and thematic developments within this research area. Probiotic encapsulation research has exhibited consistent expansion, with 89% of the publications generated in the past decade. China leads in single-country publications, while nations like the USA and Australia demonstrate robust international collaborations. Despite this growth, the field remains dispersed, with the top ten authors contributing only 7% of total publications. This fragmentation indicates diverse research directions but also highlights the absence of a centralized network of prominent contributors or institutions.

The intellectual core of probiotic encapsulation research centers around three primary areas: encapsulation materials and technologies, functional food applications, and therapeutic delivery mechanisms. Influential journals, such as Food Hydrocolloids, LWT – Food Science and Technology, and Journal of Food Engineering, have played crucial roles in advancing the field. Seminal works by researchers like Burgain et al. [49] and Kailasapathy [52] have been instrumental in developing scalable encapsulation technologies and demonstrating their integration into functional food systems. Recent advancements emphasize co-encapsulation techniques and precision delivery systems, which combine probiotics with bioactive compounds like prebiotics and polyphenols to maximize therapeutic benefits. Emerging themes, including gut-brain axis modulation and personalized nutrition, highlight the expanding applications of probiotics in addressing global health challenges.

4.2 Future trajectories

This study provides a comprehensive overview of the global research landscape on probiotic encapsulation, offering valuable insights into current trends, key contributors, and thematic progressions. However, the analysis has certain limitations. It relies solely on data from the Scopus database, which, although extensive, may exclude significant studies indexed in other repositories like Web of Science or PubMed. Future analyses should integrate data from multiple sources to achieve a more exhaustive understanding.

Several promising research directions emerge from this analysis:

4.2.1 Sustainable encapsulation materials

As sustainability gains global importance, there is a need for innovative, eco-friendly, and cost-efficient encapsulation materials. Future studies should explore natural polymers, biodegradable solutions, and the repurposing of food by-products to meet sustainability goals.

4.2.2 Personalized probiotic solutions

Advances in bioinformatics and microbiome research create opportunities for developing probiotics tailored to individual needs. Further investigation is required to identify optimal strains and delivery systems for precision nutrition and therapeutic interventions.

4.2.3 Leveraging emerging technologies

Cutting-edge technologies such as nanotechnology, artificial intelligence, and 3D printing hold potential for revolutionizing encapsulation processes. These tools can enhance encapsulation precision, scalability, and efficiency, driving innovation in functional food products.

4.2.4 Fostering interdisciplinary collaboration

Addressing the multifaceted challenges of probiotic encapsulation requires collaboration across disciplines, including material science, microbiology, and nutrition. Multidisciplinary efforts will be crucial in advancing the field and overcoming existing barriers.

4.2.5 Quantitative and longitudinal research

While qualitative insights have been valuable, there is a growing need for quantitative and long-term studies to assess the safety, efficacy, and health outcomes of encapsulated probiotics across diverse populations and conditions.

4.2.6 Exploration of broader applications

Emerging themes such as gut-brain axis modulation, immune health, and metabolic disorders provide new avenues for research. Clinical validation and studies on consumer acceptance will be vital for translating these applications into practical solutions.

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