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Exploring the Frontier: A Global Bibliometric Review of Rice Bran as Functional Food

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ABSTRACT

This bibliometric review provides a concise overview of global research trends on rice bran as a functional food. Rice bran, valued for its essential fatty acids, proteins, dietary fibre, vitamins, and antioxidants, has been increasingly studied for its potential health benefits, is recognised for its potential in preventing cardiovascular and chronic diseases. Despite its nutritional benefits and emerging research interest, comprehensive insights into the global research trends, remain fragmented. Firstly, extracting data from Scopus from 1956 to 2023, and followed by visualization tools such as VOSviewer and Scopus Analyser, this analysis maps the evolution of rice bran research, identifying key themes, contributors, and geographic distributions. The analysis highlights key research centres in the United States, China, and India and dominant themes such as dietary fibre, antioxidant activity, digestibility and fermentation. Food Chemistry emerges as the most cited journal. This study categorizes research into nine clusters, including nutrient utilisation, antioxidant properties, nutrition and fermentation, enzymatic and microbial interaction in nutrition, functional and sensory properties, dietary fiber and gut health, antioxidant activity and mineral interaction, bioactive compounds and health benefits like cancer prevention. This review maps the intellectual landscape, identifies gaps, and suggest opportunities for future research. This overview is crucial for fostering integrated development and innovation in the functional food sector.

1. Introduction

Rice bran (RB), is a by-product of the rice milling and polishing process. They are rich sources of macronutrients such as proteins, lipids, vitamins, and fibres, and some micronutrients such as

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minerals and vitamins. Typically, RB contains 12-25% fat, 11-17% protein, 10-15% moisture, and 5-35% total dietary fibre. RB also contains phenolic compounds, tocotrienols, tocopherols, γ-oryzanol, sterols, vitamins, and various antioxidants, which contribute to its health benefits, including anticancer, antidiabetic, anti-inflammatory, and hypolipidemic effects [1-3]. The bioactive compounds in RB, such as phenolic acids and flavonoids, exhibit significant antioxidant activities, which can be enhanced through fermentation and enzymatic treatments [4,5]. RB's potential extends to its use in managing metabolic ailments, including diabetes, cardiovascular diseases, and obesity, by modulating the host microbiome and maintaining eubiosis [1]. Additionally, RB-derived arabinoxylan compounds (RBAC) have shown promise in supporting immune health, reducing oxidative stress, and improving conditions like chronic fatigue syndrome, irritable bowel syndrome, and rheumatoid arthritis [2,4]. RB's versatility in the food industry is evident in its applications as a gluten flour substitute, stabilizer, emulsifying agent, and protein stabilizer, enhancing the nutritional profile and functional properties of various food products [2,6,7]. Moreover, RB protein, known for its hypoallergenic properties, has been effectively used in low-fat dairy desserts, offering a viable alternative for individuals with milk protein allergies [8]. Despite its underutilization, the growing body of research underscores the potential of RB as a cost-effective, nutrient-dense ingredient that can contribute to health promotion and disease prevention, warranting further exploration and integration into functional food of rice bran formulations.

The bibliometric analysis of rice bran research reveals a diverse and evolving field with significant contributions across various domains. The research on rice bran has shown linear growth, particularly in the context of its health benefits, such as immunomodulation, anticancer properties, hepatoprotection, anti-inflammation, and antioxidation [7]. The majority of studies focus on the rice bran arabinoxylan compound (RBAC), derived from rice bran and enzymatically treated with Lentinus edodes mycelium, which has been extensively studied for its immunomodulating effects and potential benefits for aging individuals [7]. The high insoluble fibre fraction in RB has limited its application in various food products as it imparts an unpleasant taste in the final products. Thus, several studies focus on improving solubility as well as altering the physicochemical, technological, and physiological properties by employing physical, chemical, and enzymatic treatments. These studies found significantly improved functionalities of rice bran fibre preparing it for a variety of applications in functional food formulations [9,10].

A bibliometric perspective offers a unique lens through which to examine the landscape of research and policy efforts aimed at functional food of rice bran from rice bran. By analyzing publication trends, collaboration networks, and co-citation networks, our study provides critical insights into how scientific advancements and public health initiatives have evolved in response to emerging challenges [11,12]. Bibliometric analyses using tools like VOSviewer and HistCite Pro have highlighted the trends and networks in rice bran research, showing a significant increase in publications and citations over the years [1,13].

The research has also expanded into the environmental impact of rice production, with studies exploring greenhouse gas emissions and sustainability practices in rice cultivation [14,15]. Additionally, the financial aspects of agricultural research, including rice bran, have been analyzed, indicating a growing interest in the economic implications and funding opportunities in this field [16]. The bibliometric data also shows a global distribution of research efforts, with significant contributions from countries like China, Japan, and the USA, and a notable increase in publications related to the material characterization of rice straw and husk composites [5,6,17]. This approach not only identifies the most influential studies and authors but also highlights geographical and institutional contributions to the field, offering a global overview of the concerted efforts on functional food of rice bran [16,18]. Overall, the bibliometric analysis of rice bran research underscores its multidisciplinary nature and the increasing recognition of its health, environmental, and economic significance.

Currently, there remains a discernible deficiency in the exploration of rice bran as a functional food. The significance of this study lies in elucidating the global research trajectories concerning rice bran, with an emphasis on its potential to serve as a functional food that introduces novel ingredients capable of enhancing health outcomes. The development of such strategies is imperative for augmenting research on rice bran, thereby optimising its application as a sustainable food resource essential for global needs. Accordingly, the objectives of this study were to: (i) evaluate the quality and productivity of existing research on rice bran as a functional food; and (ii) critically examine the impact of the literature, delineate research networks, and identify prevailing gaps.

2. Methodology

Bibliometrics involves the collection, management, and analysis of bibliographic information from scientific publications [19-21]. It includes general descriptive statistics like publishing journals, publication year, and main author classification [22], and advanced techniques like document co-citation analysis. A thorough literature review requires an iterative process of identifying relevant keywords, searching literature, and detailed analysis to create a comprehensive bibliography and achieve reliable results [23]. This study focused on top-tier publications to gain valuable insights into the theoretical perspectives shaping the research field. To ensure data reliability, data was collected from the SCOPUS database [12,24]. Only articles from rigorously peer-reviewed academic journals were included, deliberately excluding books and lecture notes [12,21,24-27]. Elsevier’s Scopus, known for its extensive coverage, was used to collect publications from 1955 to 2023 for analysis.

The study employed a screening sequence to determine search terms for retrieving articles. It started by querying the Scopus database using the boolean search string: TITLE-ABS-KEY (("rice bran" AND ("fibre*" OR "dietary fibre" OR "functional food of rice bran*"))) AND PUBYEAR > 1955 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (LANGUAGE , "English")) [27]. This initial search yielded 1315 articles. The search terms were then refined to focus on the functional food application of rice bran, reducing the results to 964 articles [28]. Further screening excluded non-English articles, conference papers, and book chapters. The final refined search string included 964 articles, which were used for bibliometric analysis [29]. As of May 2024, all relevant articles from the Scopus database on functional food applications of rice bran were examined in this study. Table 1 shows the search string used in this study using Scopus database.

Table 1
Search query Scopus database demonstrates the search string used in this study

Scopus	TITLE-ABS-KEY (("rice bran" AND ("fibre*" OR "dietary fibre" OR "functional food of rice bran*"))) AND PUBYEAR > 1955 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (LANGUAGE , "English"))

Bibliometrics involves the collection, organization, and analysis of bibliographic data from scientific publications [8,9,30-32]. It includes basic descriptive statistics, such as publishing journals, publication year, and main author classification [31,33], as well as advanced techniques such as document co-citation analysis. The criteria for selecting documents for bibliometric analysis is summarized in Figure 1.

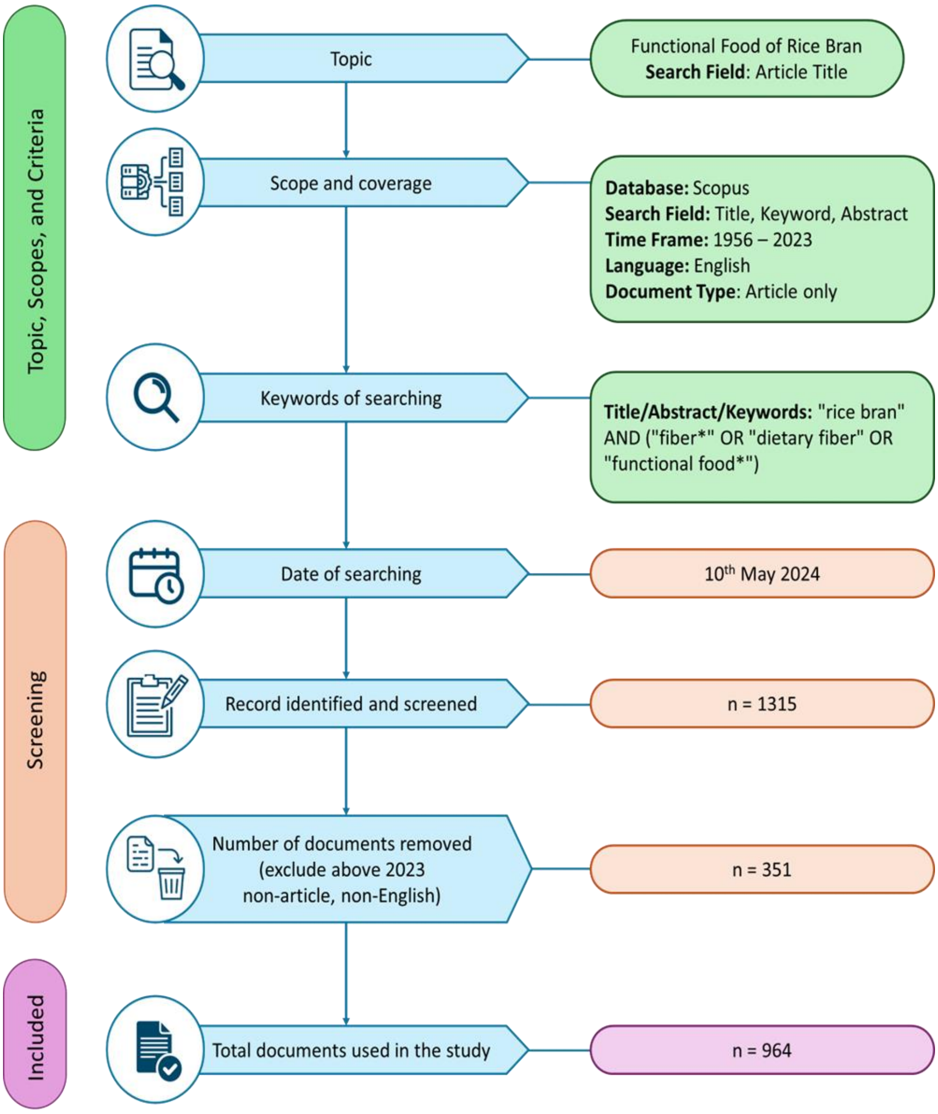

Fig. 1. Criteria for selecting documents for bibliometric analysis

Datasets including publication year, title, author name, journal, citation count, and keywords from 2013 to December 2023 were sourced from the Scopus database and analyzed using VOSviewer software version 1.6.19 and their inclusion and exclusion criteria are summarized in Table 2. This software facilitated analysis and map creation through VOS clustering and mapping methods. VOSviewer, an alternative to the Multidimensional Scaling (MDS) approach [34], aims to place items in a low-dimensional space so their distance accurately reflects their relatedness and similarity [35]. Unlike MDS, which calculates similarity measures such as Jaccard indexes and cosine, VOS uses a more suitable method for normalizing co-occurrence frequencies [34].

Table 2
Summary of selection criteria for searching using Scopus database

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	1955-2024	< 1955, >2024
Literature type	Journal (article)	Conference, book
Publication stage	Final	In press

The VOSviewer uses a three-stage process for bibliometric analysis to visualize complex datasets in two dimensions. First, a similarity matrix is created by normalizing the co-occurrence matrix with association strength as the similarity metric between item pairs. The similarity (S_{ij}) is calculated with the Eq. (1):

$$S_{ij} = \frac{c_{ij}}{w_i \quad w_j} \tag{1}$$

where C_{ij} signifies the number of times of co-occurrences, and W_i and W_j represent the individual occurrences of the respective items *i* and *j* . Next, the matrix is subjected to VOS mapping, which aims to minimize the weighted sum of squared distances between all item pairs, ensuring accurate low-dimensional representation [28] . This optimization is expressed by Eq. (2):

$$\min V(x_1, \ldots, x_n) = \sum_{i<j} S_{ij} \ \|x_i - x_j\|^2, subject\ to\ \frac{2}{n(n-1)} \sum_{i<j} \|x_i - x_j\| = 1 \tag{2}$$

In VOSviewer's framework, $X_i=(X_{i1},X_{i2})$ represents the coordinates of item on a two-dimensional map, where ‖·‖ signifies the Euclidean norm. The term is the total number of items to be positioned on the two-dimensional map. This detailed procedure allows VOSviewer to visualize the bibliometric network, showing connections between entities like authors, articles, and keywords [36]. The strength of these connections is measured by the association strength metric, providing insights into collaborative dynamics and thematic concentrations in the research field [37]. This method allows for visual examination of research trends and relationships, clarifying overarching patterns in scholarly data [38].

3. Results

The findings and related discussions on this study are presented based on Research Question or (RQ 1), (RQ 2), (RQ3), (RQ4), (RQ5), (RQ6) and (RQ7). Here are the points discussed according to RQ 1 to RQ 7.

3.1 RQ1: What are the Research Trends in Functional Food of Rice Bran Studies According to the Year of Publication?

Figure 2 shows that the trend of documents' production based on the year collected through the Scopus Analyser. From 1955 to 1985, research on rice bran as a functional food was minimal, with only a few publications indicating early exploration. Between 1986 and 2005, interest grew steadily as initial breakthroughs highlighted its nutritional benefits. From 2006 to 2015, the number of publications increased significantly due to advancements in food science and a heightened awareness of health benefits. The timeframe between 2016 and 2023 experienced a significant upsurge in research activity, reaching its peak around 2021, driven by enhanced funding, industry collaborations, and key discoveries. Currently, the trend continues to grow, focusing on innovative uses and the health-promoting properties of rice bran.

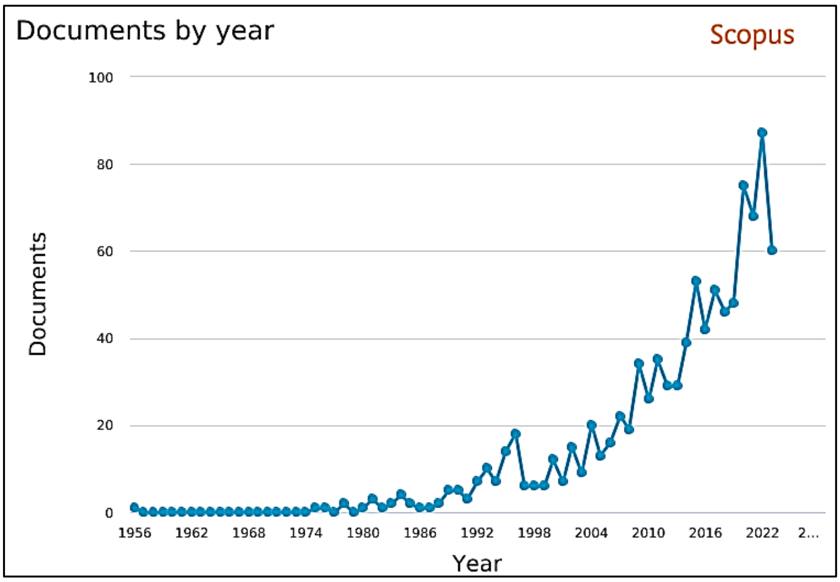

Fig. 2. Trend of documents by year

3.2 RQ2: What is the Trend of Article Earnings Based on the Subject Area?

The bibliometric analysis of 964 research documents on the functional food of rice bran, as depicted in the Scopus pie chart in Figure 3, underscores the multifaceted and interdisciplinary nature of this research area. Figure 3 shows the breakdown of the distribution of studies based on functional food of rice bran of rice bran performed based on related subjects.

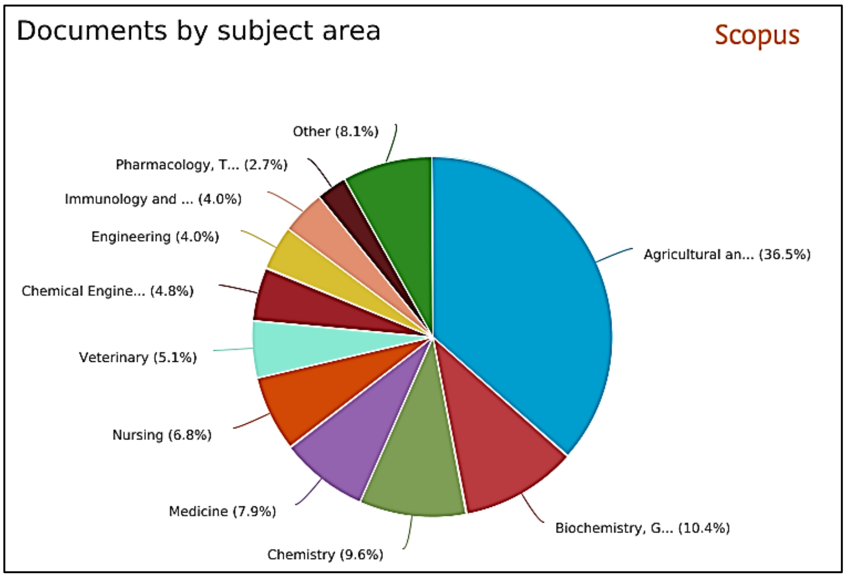

Fig. 3. Documents by subject area

The largest segment, comprising 36.5% of the documents, is dedicated to Agricultural and Biological Sciences, highlighting the emphasis on cultivation, genetic improvement, and biological properties of rice bran. This research is crucial for optimizing rice bran production, understanding its nutrient composition, and enhancing its use in agriculture, leading to more sustainable farming practices and improved crop yields. Similarly, the significant focus on Biochemistry, Genetics, and Molecular Biology (10.4%) reflects the interest in understanding the molecular mechanisms and genetic factors that contribute to the health benefits of rice bran. This knowledge can facilitate the development of genetically modified rice with enhanced functional properties and the identification of bioactive compounds with potential health benefits.

A substantial portion of research is also directed towards the chemical and medical fields, with Chemistry (9.6%) and Medicine (7.9%) representing key areas of focus. The exploration of the chemical composition and properties of rice bran includes identifying and characterizing bioactive compounds, understanding their stability and interactions, and developing methods for their extraction and quantification. This is essential for developing functional foods and nutraceuticals. Concurrently, medical research emphasizes the health benefits of rice bran, such as its role in preventing or managing diseases like diabetes, cardiovascular diseases, and cancer. This focus on health benefits is further supported by research in Nursing (6.8%) and Veterinary (5.1%), highlighting the potential applications of rice bran in human and animal health. For humans, this could include dietary interventions and health promotion, while for animals, it could improve livestock health and productivity, impacting food security and agricultural economics.

Engineering and technological research also play a significant role, with Chemical Engineering (4.8%) and Engineering (4.0%) indicating advancements in technologies and processes for processing rice bran, enhancing its functional properties, and incorporating it into various food products. This includes developments in extraction methods, preservation techniques, and formulation of functional foods. Additionally, research in Immunology and Microbiology (4.0%) suggests an interest in the effects of rice bran on the immune system and its antimicrobial properties, leading to the development of rice bran-based functional foods that support immune health and serve as natural preservatives. Lastly, the research in Pharmacology, Toxicology, and Pharmaceutics (2.7%) is vital for exploring the pharmacological effects, safety, and potential toxicities of rice bran, ensuring that rice bran-based products are safe for consumption and understanding their mechanisms of action. The diverse nature of the 'Other' category (8.1%) indicates emerging and interdisciplinary research areas that may not fit neatly into traditional categories, further illustrating the broad and comprehensive scope of research on rice bran functional food.

In summary the distribution of research across these various disciplines highlights the comprehensive and interdisciplinary approach to studying rice bran as a functional food. This holistic research effort is essential for unlocking the full potential of rice bran in improving human health, enhancing agricultural practices, and developing innovative food products. The findings can guide future research priorities, inform policy decisions, and drive the development of new technologies and products that capitalize on the health benefits of rice bran.

3.3 RQ3: What is the Title of the Article that has the Highest Number of Citations by Ranking?

The bibliometric data presented in Table 3 underscore the influential contributions to rice bran research, delineating the primary scientific focal points. This body of research, accruing significant citations between 1956 and 2023, has been instrumental in advancing our comprehension of rice bran's role as a functional food [39-48].

The top-ranked article, "Functional properties of dietary fibre prepared from defatted rice bran", published in 2000 in "Food Chemistry," has received 402 citations [34]. It discusses the dietary fibre properties of defatted rice bran, highlighting its nutritional benefits. The second-ranked article, "Changes in whole-grain, bran, and cereal fibre consumption by the US population", published in 2004 in the "American Journal of Clinical Nutrition," has 356 citations [35]. It examines dietary trends in the US regarding fibre consumption. The third-ranked article, "Rice Bran: A Novel Functional Ingredient", published in 2014 in "Critical Reviews in Food Science and Nutrition," has 287 citations [36]. It reviews the potential of rice bran as a functional food ingredient.

In summary, the most-cited papers on the functional food of rice bran significantly enhance scholarly knowledge by providing crucial insights into its nutritional benefits, health implications, practical applications, and environmental uses. They lay the groundwork for ongoing and future research, contributing to scientific progress and practical innovations in multiple domains.

Table 3
Top 10 number of citations

Title	Year	Name of journal	Volume	Cited by	References
Functional properties of dietary fibre prepared from defatted rice bran	2000	Food Chemistry	68	402	[39]
Changes in whole-grain, bran, and cereal fibre consumption in relation to 8-y weight gain among men	2004	American Journal of Clinical Nutrition	80	356	[40]
Rice Bran: A novel functional ingredient	2014	Critical Reviews in Food Science and Nutrition	54	287	[41]
Cholesterol-lowering effects of oat β-glucan	2011	Nutrition Reviews	69	274	[42]
Characteristics of low-fat meat emulsion systems with pork fat replaced by vegetable oils and rice bran fibre	2009	Meat Science	82	246	[43]
Rice: importance for global nutrition	2019	Journal of Nutritional Science and Vitaminology	65	234	[44]
Obesity, the Metabolic Syndrome, and Type 2 Diabetes in Developing Countries: Role of Dietary Fats and Oils	2010	Journal of the American College of Nutrition	29	226	[45]
Phytochemicals and antioxidants capacities in Rice Bran of different colour	2011	Journal of Food Science	76	221	[46]
The removal of basic dyes from aqueous solutions using agricultural by-products	2008	Journal of Hazardous Materials	157	216	[47]
Structural characteristics and functional properties of rice bran dietary fiber modified by enzymatic and enzyme-micronization treatments	2017	LWT	75	212	[48]

3.4 RQ 4: What is the Map of Co-Authorship by Authors?

In the co-author's citation analysis section, co-authors serve as the primary unit of analysis. Selection criteria for the authors included in this study required a minimum of five published documents and at least ten citations. A total of 37 authors out of 3735 authors met the threshold and were chosen for co-citation network analysis. The total link strength was calculated for each of these 37 authors, however, only the top five are reported in Table 4. Liu Lei emerged as the author with the highests total link strength, registering 54 links alongside 292 citations. Following Liu Lei, Choi Yun-Sang and Kim Cheon-Jei held the second and third positions, with total link strengths of 39 and respective citations of 821. Zhang Mingwei and Zhang Ruifen rounded out the top five, each with a link strength of 38 and 520 citations.

Table 4
The five prominent authors with the highest total link strength

Authors	Documents	Citations	Total link strength
Liu, Lei	11	292	54
Choi, Yun-Sang	9	821	39
Kim, Cheon-Jei	9	821	39
Zhang, Mingwei	9	520	38
Zhang, Ruifen	9	520	38

Figure 4 presents a network visualization of prominent co-citation authors, offering insight into the structure of collaborative networks. In this diagram, nodes represent authors, with the size of each node corresponds to the author's publication volume or their centrality in the network, with larger nodes indicating more prolific or central figures. The lines between nodes signify co-authorship links, with their thickness indicating the extent of collaboration; where thicker lines suggest a higher number of co-authored works. Together, these visual elements provide a comprehensive view of the network, highlighting key contributors and the nature of their collaborations.

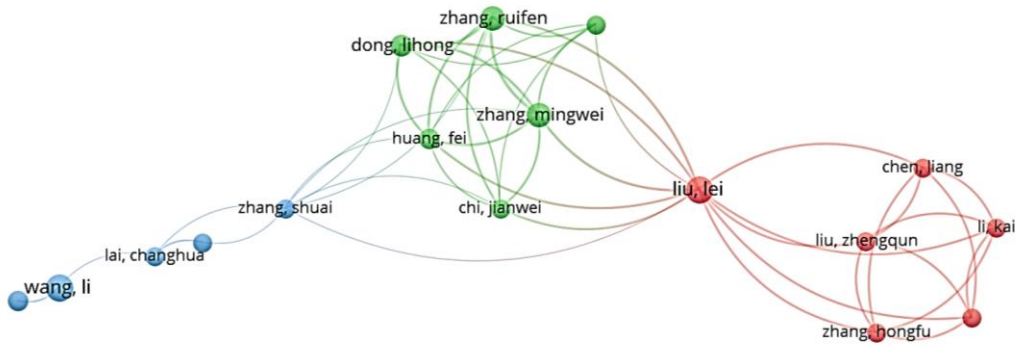

Fig. 4. Network visualization map of co-authorship

Figure 4 provides a detail mapping of three principal co-authorship networks in rice bran research, each focusing on specific aspects of this functional food. The red cluster focuses on functional components and health benefits, the green cluster on nutritional composition and food applications, and the blue cluster on processing techniques and product development, particularly innovative methods and the creation of new rice bran-based products. Additionally, the figure also highlights Inter-Cluster Collaboration that engage in cross-disciplinary projects, integrating health, nutrition, and processing research. These collaborations often facilitated by joint research centres, illustrate the collaborative efforts across various institutions. Furthermore, partnership between academia and the food industries are highlighted as strategic alliances aiming to transform research findings into commercial products.

Together, these themes provide a comprehensive framework for studying rice bran as a functional food, addressing its biochemical properties, practical applications in food products, and implications for health outcomes.

3.5 RQ 5: What are co-Authorship Countries' Collaboration?

Figure 5 illustrates the co-authorship network of countries involved in functional food research focusing on rice bran. The network visualization highlights the collaborative relationships between researchers from various countries. Out of 75 countries, 35 met threshold with minimum of 5 documents per country and minimum of 40 citations. The top five countries with the highest co-authorship collaboration are summarized in Table 5.

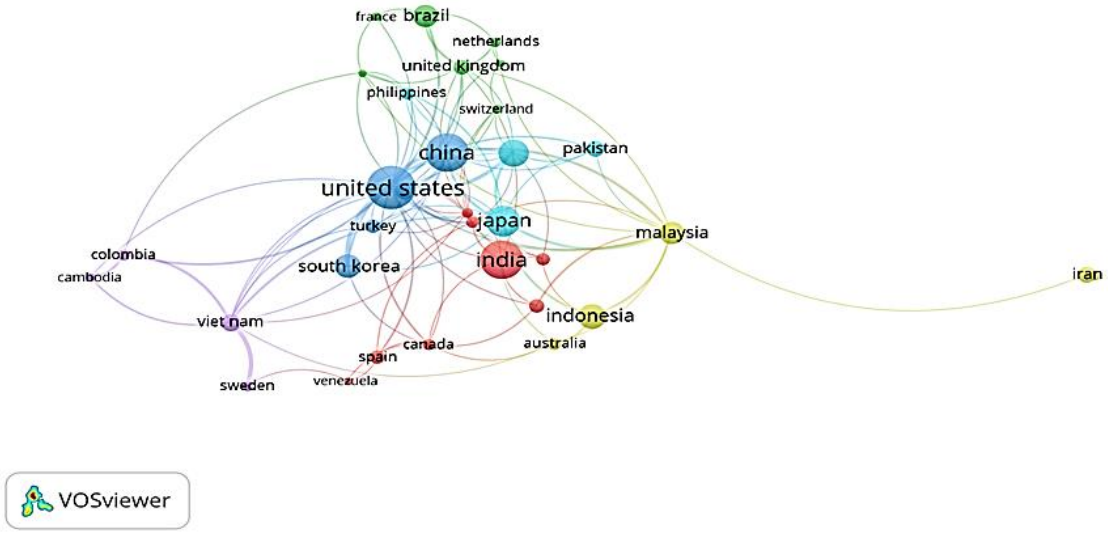

Fig. 5. Co-authorship within countries

Table 5
The five prominent countries of co-authorship by countries

Country	Documents	Citations	Total link strength
United States	168	7830	61
China	127	3908	33
Japan	86	1680	31
Vietnam	28	357	25
Malaysia	44	1303	24

The size of the nodes represents the number of publications from each country, while the thickness of the links indicates the strength of the co-authorship connections. The significance of this information lies in understanding the global research dynamics and identifying key players in the field. The network visualization map categorizes global rice bran research into six co-authorship network clusters, each emphasizing distinct thematic and geographic concentrations as summarized in Table 6 and Figure 5.

Each cluster highlights the diverse and interdisciplinary nature of rice bran research, underlining its global importance across scientific and commercial domains. Figure 5 display the co-authorship within countries highlighting six clusters based on colour, such as blue, red, green, green-yellow, purple and orange. Understanding these collaborative trends is crucial for strategic planning in rice bran research. It assists in identifying potential international collaborators, fostering new partnerships, and boosting the global exchange of knowledge and innovations. Furthermore, the network can guide funding agencies and policymakers in supporting key collaborations and facilitating joint research projects. Such actions are key to accelerate progress in the functional food application of rice bran, ultimately enriching both academic and commercial pursuits.

Table 6
The major cluster of countries of co-authorship and their scope of research

Cluster	Countries	Scope of research
Blue	China, Egypt, South Korea, Turkey, and the United States	Advancing rice bran processing technologies and developing new products
Red	India, Bangladesh, Canada, Germany, Nigeria, Spain, Taiwan, and Venezuela	Focuses on foundational genetic studies and agronomic traits of rice bran.
Green	Brazil, Denmark, France, the Netherlands, Sri Lanka, Switzerland, and the United Kingdom	Investigates the nutritional composition and health benefits of rice bran, aligning with its potential as a functional food.
Green-yellow	Australia, Indonesia, Iran, Italy, and Malaysia	Explores innovative food applications and sustainable agricultural practices involving rice bran.
Purple	Cambodia, Colombia, Sweden, and Vietnam	Focus is on traditional uses and local market adaptations of rice bran.
Orange	Japan, Pakistan, the Philippines, and Thailand,	Research here delves into the bioactive components of rice bran and their specific health implications in Asian diets.

3.6 RQ 6: What are Co-Citation Trends Based on Sources?

Figure 6 shows the trend of resources offering the production of articles related to aspects of rice bran research. Out of 10802 sources of publication, 216 journals met the threshold with minimum of 20 citations. The network mapping based on co-citation by cited sources for research on functional food rice bran illustrates how frequently pairs of sources are cited together in the scientific literature (Figure 6). Each node represents a cited source (journal or publication), and the connections (edges) between nodes indicate co-citation relationships. The size of the node reflects the number of citations, and clusters of nodes represent groups of sources that are frequently cited together, indicating thematic relationships.

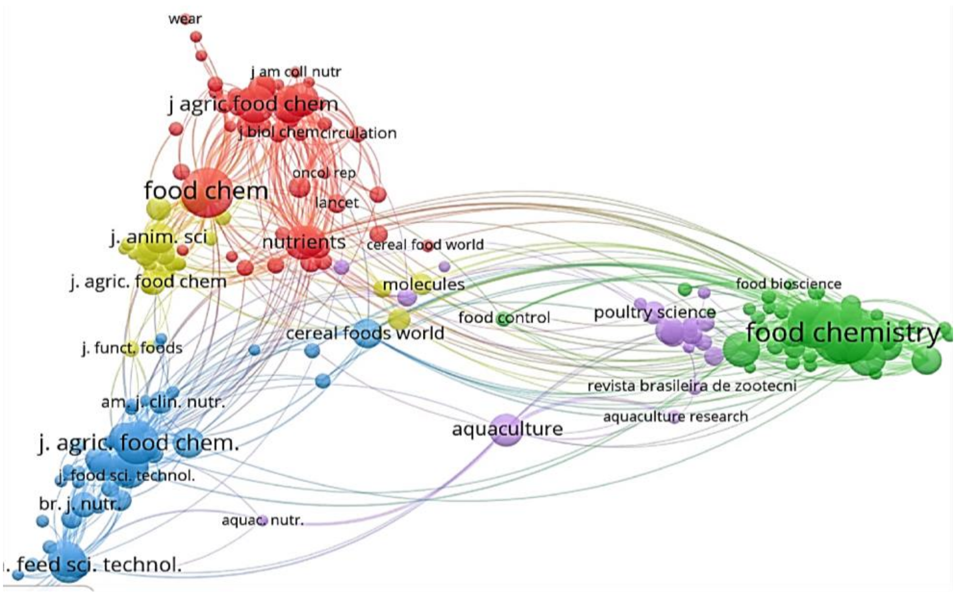

Fig. 6. Networking mapping based on co-citation by cited sources

Key themes and trends have emerged from the data analysis based on 5 categories as shown in Table 7. The green cluster, dominated by "Food Chemistry," indicates a significant focus on understanding the chemical and nutritional properties of rice bran. The blue cluster highlights the importance of rice bran in human health and its functional properties in food science. The red cluster suggests a broad, interdisciplinary research approach, incorporating agricultural, nutritional, and biochemical studies. The yellow cluster emphasize the use of rice bran in animal science and animal nutrition, while the purple cluster focuses on applications of rice bran in aquaculture feed, highlighting its benefits for fish and other aquatic species. Overall, this network mapping provides a visual representation of the research landscape on functional food rice bran, illustrating the interconnections between various research themes and highlighting key sources that are central to the field.

Table 7
The clusters and key sources in rice bran functional food research

Cluster	Key sources	Characteristics
Green cluster	Food Chemistry	Focuses on chemical and biochemical aspects of rice bran, including composition, nutritional properties, and food science applications.
Blue cluster	Journal of Functional Foods, American Journal of Clinical Nutrition	Explores functional aspects and health benefits of rice bran, including its impact on human health and clinical nutrition.
Red cluster	Journal of Agricultural and Food Chemistry, Nutrients	Covers agricultural, nutritional, and biochemical research, with an interdisciplinary approach to rice bran.
Yellow cluster	Journal of Animal Science, Journal of Agricultural and Food Chemistry	Emphasizes animal science and the use of rice bran in animal nutrition, focusing on its effects on animal health and productivity.
Purple cluster	Aquaculture, Revista Brasileira de Zootecnia	Focuses on applications of rice bran in aquaculture feed and its benefits for fish and other aquatic species.

3.7 RQ7: What is the Co-Occurrence of Authors' Keywords Related to the Study?

As shown in Figure 7, the network visualization map of authors' keywords' co-occurrence illustrates these diverse focus areas and the interconnected nature of research on rice bran. This visual representation aids in comprehending the connections between different themes and highlights key keywords within the research landscape. Clusters 1, 3, and 6 focus on using rice bran and its derivatives in animal feed, emphasizing their nutritional value, digestibility, and impact on growth performance. Clusters such as Cluster 2 and Cluster 7 emphasize antioxidant activities and bioactive compounds, highlighting a strong interest in the health benefits and functional properties of rice bran.

Additionally, Clusters 4 and 6 examine the interaction between dietary fibers, enzymes, and the microbiome, showcasing the importance of microbiological and enzymatic processes in nutrition. Cluster 5 covers the functional properties of rice bran in food products, including its role in improving texture, stability, and sensory attributes. Cluster 8 uniquely addresses bioactive compounds and their direct health effects, particularly concerning obesity and γ-oryzanol. Cluster 9 is distinct in concentrating solely on the chemopreventive properties of rice bran, especially in relation to colorectal cancer, highlighting a specific health application not extensively covered in other clusters.

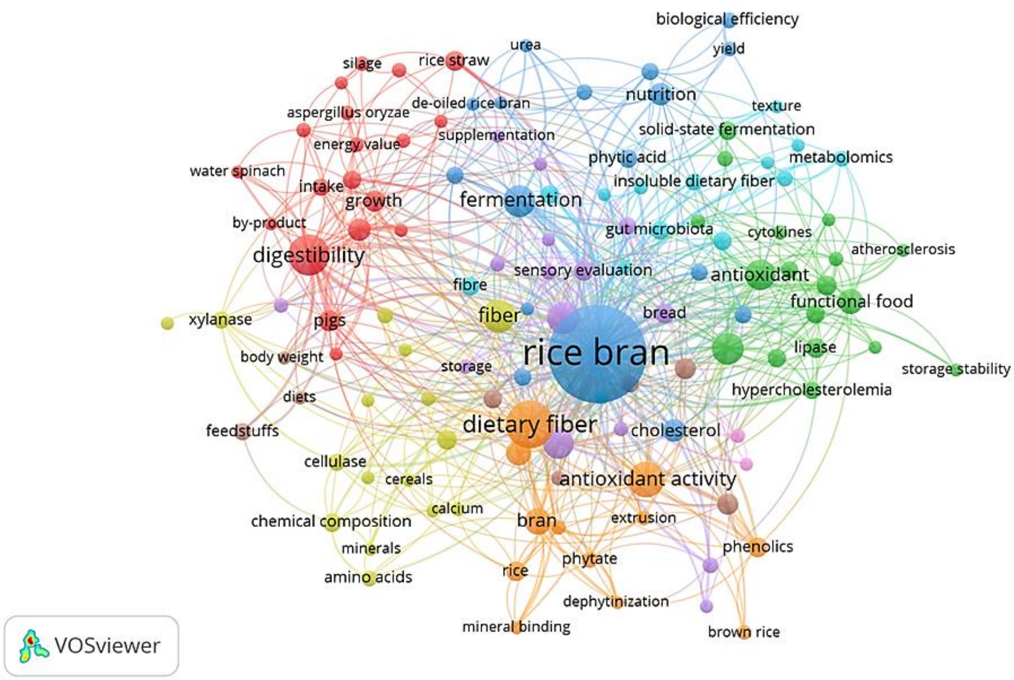

Fig. 7. Network visualization map of authors' keywords' co-occurrence

This research aims to integrate these diverse themes into a cohesive exploration of rice bran's potential, addressing gaps such as its underutilization in food products, detailed mechanisms of action, and standardized treatment processes. By covering topics like regulatory and safety assessments, consumer acceptance, and market potential, the research will fill crucial gaps that existing studies only briefly touch upon. Including robust clinical evidence and human trials will provide a solid scientific basis for the health benefits of rice bran, enhancing its credibility and practical applicability in both the food and health industries. The summary of different themes and the highlights of keywords in rice bran research is represented in Table 8.

Table 9 provides a comprehensive synthesis of the functional and nutritional potentials of rice bran across diverse applications, emphasizing significant findings and future research opportunities. Rice bran demonstrates considerable benefits in enhancing nutrient utilization in animal feed, improving antioxidant and functional properties in food products, and promoting gut health through dietary fiber. Enzymatic and microbial interventions have been shown to boost its digestibility and nutrient bioavailability, while its bioactive compounds, such as γ-oryzanol, exhibit promising anti-obesity and metabolic health benefits. Moreover, rice bran's chemopreventive properties suggest its potential role in reducing colorectal cancer risk, supported by preclinical evidence. Despite these advancements, significant research gaps remain, such as the need for standardized methodologies in evaluating bioavailability, scaling fermentation processes, and exploring long-term health impacts across populations. Future studies should focus on optimizing processing methods, conducting clinical trials to validate health benefits, and scaling up industrial applications to harness rice bran's potential fully in food, feed, and health contexts.

Table 8
Summary of keywords and clusters in rice bran research

Cluster	Number of items	Focus area	Keywords	Explanation
1	19	Nutrient utilization in animal feed	Aspergillus oryzae, by-product, by-products, degradability, digestibility, energy, energy value, enzymes, growing pigs, growth, in vitro, intake, nutrient utilization, nutritional value, performance, pigs, rice straw, silage, water spinach	Focuses on the use of rice bran and its by-products in animal feed, highlighting its nutritional value and impact on animal growth and performance.
2	18	Antioxidant properties and functional foods	antioxidant, atherosclerosis, black rice bran, cytokines, fatty acids, fermented rice bran, functional food, functional foods, hypercholesterolemia, inflammation, lipase, nutraceuticals, oryza sativa, oxidative stress, phytochemicals, rice bran oil, solid-state fermentation, storage stability	Emphasizes the antioxidant properties of rice bran and its applications in functional foods, addressing health benefits such as reducing inflammation and hypercholesterolemia.
3	17	Nutrition and fermentation in food products	biological efficiency, broiler, cholesterol, cookies, de-oiled rice bran, dietary fibers, fermentation, growth performance, nutrition, phytase, phytic acid, protein, response surface methodology, rice bran, urea, wheat flour, yield	Discusses the use of rice bran in human food products, particularly in fermented foods, and its effects on nutrition and health.
4	16	Enzymatic and microbial interactions in nutrition	amino acids, arabinoxylan, calcium, cellulase, cereals, chemical composition, enzymatic hydrolysis, ferulic acid, fiber, microbiome, in vitro digestibility, minerals, nutrient digestibility, rice bran fiber, starch, xylanase	Explores how enzymatic treatments and microbial interactions enhance the nutritional properties of rice bran, focusing on digestibility and bioavailability of nutrients.
5	15	Functional and sensory properties in food products	biscuits, bread, cereal bran, defatted rice bran, dietary fiber, extrusion cooking, functional, functional properties, physicochemical properties, sensory evaluation, soluble dietary fiber, stabilization, stabilized rice bran, storage, supplementation	Covers the functional properties of rice bran in food products, including its role in improving texture, stability, and sensory attributes.
6	14	Dietary fiber and gut health	broilers, fiber, gut microbiota, in vitro digestion, insoluble dietary fiber, metabolomics, microbiota, phenolic compounds, prebiotic, probiotics, rice bran dietary fiber, short-chain fatty acids, texture	Investigates the benefits of rice bran dietary fiber on gut health, including its prebiotic effects and impact on gut microbiota.
7	12	Antioxidant activity and mineral interactions	antioxidant activity, bran, brown rice, dephytinization, dietary fiber, extrusion, mineral binding, phenolics, phytate, rice, wheat, wheat bran	Highlights the antioxidant activities of rice bran and its interaction with minerals, which

				contribute to its health benefits.
8	8	Bioactive compounds and health benefits	antioxidants, bioactive compounds, body weight, diets, feedstuffs, lactic acid bacteria, obesity, γ-oryzanol	Focuses on specific bioactive compounds in rice bran, such as γ-oryzanol, and their potential health benefits, including weight management and anti-obesity effects.
9	2	Cancer prevention	chemoprevention, colorectal cancer	Discusses the potential of rice bran in cancer prevention, particularly in reducing the risk of colorectal cancer through chemopreventive properties.

Table 9

Comprehensive analysis of functional and nutritional applications of rice bran: Significant findings and future research directions

Cluster	Focus area	Significant findings	Methodologies	Research gaps	Future research
1	Nutrient utilization in animal feed	Rice bran enhances animal feed by improving nutrient absorption and positively impacting growth performance in animals.	Enzymatic hydrolysis, in vitro digestibility studies, feeding trials	Limited exploration of long-term effects and optimal inclusion ratios of rice bran in diverse livestock diets.	Investigate long-term effects of rice bran on different species and optimize inclusion ratios in feed formulations.
2	Antioxidant properties and functional foods	Rice bran provides potent antioxidant benefits, aiding in reducing oxidative stress and promoting cardiovascular health.	Chemical assays (DPPH, FRAP), storage stability tests	Need for consistent methodology in evaluating bioavailability of antioxidants in functional food formulations.	Explore bioavailability and efficacy of rice bran antioxidants in real-world functional food applications.
3	Nutrition and fermentation in food products	Fermentation improves the nutritional content and sensory properties of rice bran, making it suitable for use in diverse food products.	Fermentation optimization, nutritional assays	Inadequate focus on scaling up fermentation processes for industrial use and its impact on sensory qualities.	Scale up fermentation processes and assess the sensory and nutritional impacts in large-scale food production systems.
4	Enzymatic and microbial interactions in nutrition	Enzymatic treatments and microbial actions significantly enhance the digestibility and bioavailability of nutrients in rice bran.	In vitro digestibility, enzyme activity assays	Insufficient understanding of enzyme synergy and microbiome changes in different	Study enzyme combinations and their interaction with microbiota to optimize nutrient availability.

				biological systems.	
5	Functional and sensory properties in food products	Stabilized rice bran improves texture, stability, and sensory attributes, making it a valuable ingredient in processed foods.	Extrusion cooking, stabilization techniques	Limited sensory evaluation across diverse populations and incorporation methods for specific food products.	Conduct sensory evaluation across diverse demographics and refine processing techniques for wider food applications.
6	Dietary fiber and gut health	Rice bran dietary fiber has prebiotic benefits, modulating gut microbiota and improving gut health through increased short-chain fatty acid production.	Metabolomic analysis, microbiota profiling	More longitudinal studies on rice bran fiber's effects on gut microbiota and systemic health.	Examine the long-term effects of rice bran fiber on microbiota composition and its systemic health implications.
7	Antioxidant activity and mineral interactions	Antioxidant properties of rice bran are complemented by its ability to interact with minerals, enhancing their bioavailability.	Mineral-binding assays, antioxidant activity tests	Lack of comprehensive data on mineral absorption changes due to rice bran interaction.	Investigate how processing methods affect antioxidant properties and mineral interactions.
8	Bioactive compounds and health benefits	Bioactive compounds like γ-oryzanol in rice bran offer anti-obesity and metabolic health benefits, demonstrating potential for functional food use.	Bioactive compound quantification, health impact studies	Minimal exploration of long-term impacts and compound stability in food systems.	Conduct studies on the stability and delivery mechanisms of bioactive compounds in functional food systems.
9	Cancer prevention	Chemopreventive properties of rice bran show promise in reducing colorectal cancer risk, with effects observed in preclinical studies.	Chemopreventi on studies, in vivo models	Limited clinical trials to validate chemopreventive effects in human populations.	Develop clinical trials to confirm rice bran's chemopreventive potential and explore molecular mechanisms.

4. Future Research Directions

Future research on rice bran should build on its demonstrated nutritional and functional properties to address global health challenges. Rice bran, a by-product of rice milling, is rich in bioactive compounds such as γ-oryzanol, phenolic acids, tocopherols, and dietary fibers, which confer numerous health benefits, including antioxidant, anti-inflammatory, and prebiotic effects. While significant advancements have been made in understanding these benefits, further scientific investigations are required to deepen knowledge about its mechanisms of action, optimize its applications, and enhance its acceptance as a functional food ingredient.

One key area for future research is clinical validation of rice bran's health benefits. Current studies suggest its potential in managing conditions such as hypercholesterolemia, obesity, and inflammation. For example, γ-oryzanol has been shown to improve lipid profiles by reducing LDL cholesterol levels, while the antioxidant properties of rice bran phenolics mitigate oxidative stress linked to chronic diseases. However, most of these findings stem from small-scale or animal studies. Large-scale, randomized controlled trials (RCTs) in diverse populations are essential to establish causality and determine the effective dosages and formulations of rice bran components. Such evidence would substantiate its claims as a functional food and facilitate its integration into clinical nutrition guidelines.

Another promising avenue is rice bran's role in gut health. Research shows that its dietary fibers, particularly prebiotic fibers, promote beneficial gut microbiota, enhance short-chain fatty acid production, and improve gut barrier function. Metabolomic studies could provide insights into how rice bran’s fiber interacts with the gut microbiome to influence systemic health outcomes, such as immune modulation and metabolic regulation. These findings could inform the development of targeted functional food products designed to support gut health.

Moreover, rice bran’s chemopreventive properties merit attention. Preliminary research indicates its potential to reduce colorectal cancer risk by modulating pathways associated with inflammation and cell proliferation. For instance, dephytinized rice bran has shown promise in enhancing mineral bioavailability and reducing pro-inflammatory cytokine production. Future research should focus on identifying specific bioactive fractions responsible for these effects and conducting human clinical trials to assess their efficacy and safety.

Consumer acceptance and market trends also necessitate research into improving the sensory and functional properties of rice bran products. Stabilization techniques, such as extrusion cooking and fermentation, can address rancidity and enhance bioactive compound bioavailability. Sensory evaluation studies should be conducted to tailor rice bran-enriched foods to consumer preferences, ensuring palatability and ease of integration into daily diets. Furthermore, functional food innovations, such as ready-to-eat products or beverages fortified with rice bran extracts, could tap into the growing demand for health-promoting foods.

Lastly, policy and industry collaboration is essential for scaling rice bran's applications. As scientific evidence accumulates, efforts to educate stakeholders about its health benefits and sustainability should be prioritized. The development of standardized guidelines for rice bran processing and labeling could boost consumer confidence and market growth. By addressing these research gaps and aligning with global health trends, rice bran holds immense potential to emerge as a cornerstone of sustainable nutrition and functional food science.

5. Conclusions

The research landscape for functional food rice bran, shown through network mapping and co-citation analysis, reveals a complex and interdisciplinary field with key focus areas and global collaborations. Future research should explore the bioavailability of rice bran's nutrients and their health effects, while also advancing biotechnological methods to enhance its nutritional profile. Additionally, investigating the specific molecular and genetic mechanisms behind rice bran's health benefits could provide deeper insights. Long-term clinical trials are necessary to confirm its health benefits and safety, solidifying its role in functional foods. Collaborative projects that bring together experts from various disciplines can lead to innovative applications and a comprehensive understanding. Exploring the socio-economic impacts of incorporating rice bran into diets worldwide would offer a broader perspective on its benefits. Further research on optimizing rice bran formulations for different species, its impact on animal health and productivity, and its environmental benefits can enhance its application in these sectors.

In conclusion, rice bran research holds immense potential for the future. Its ability to improve human and animal health, contribute to food security, and provide environmental benefits underscores its importance. By continuing to explore and understand its applications and benefits, rice bran can lead to significant advancements in both the food industry and public health. The ongoing and future research efforts are crucial for maximizing the potential of rice bran as a functional food, ensuring its role in promoting sustainable and health-promoting diets worldwide.

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