REVIEW ARTICLE

FOOD
SCIENCE TODAY

Lactic acid bacteria in wheat fermentation: A bibliometric analysis of antioxidant peptide production

Bactérias lácticas na fermentação do trigo: uma análise bibliométrica da produção de peptídeos antioxidantes

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Abstract

The increasing demand for functional foods has led to an interest in fermentation processes that enhance the production of antioxidant peptides. This study aimed to perform a bibliometric analysis of lactic acid bacteria (LAB) used in the fermentation of wheat to produce antioxidant peptides. To achieve this, data from 2010 to 2023 were gathered from the Web of Science® database, focusing on publications related to LAB, wheat proteins, and antioxidant peptides. The search results were analyzed using the bibliometrix R package, which allowed for an in-depth examination of research trends, collaborations, and influential studies. Results indicated increased research activity, with an average annual growth rate of 13.18% and contributions from countries such as China and Italy. The primary focus areas included fermentation methods, peptide production, and health-related applications of bioactive compounds. Collaboration networks highlighted the importance of international partnerships in advancing this field. The results provided insights into the development and application of LAB in food science, emphasizing the potential of bioactive peptides produced from wheat in promoting health through antioxidant activity. This study contributes to understanding the research landscape and the future potential of using LAB to produce functional food ingredients.

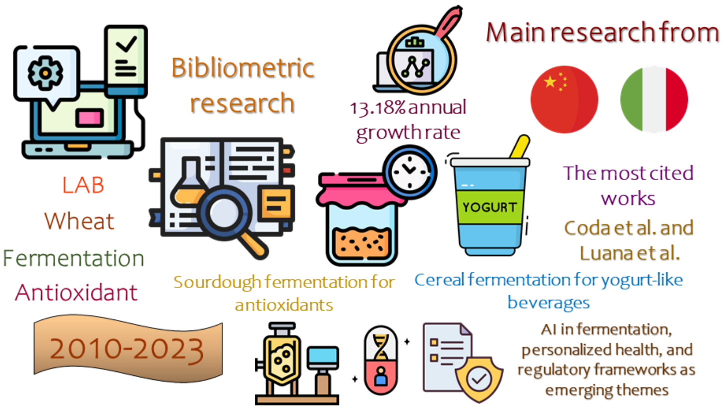
Keywords: Lactic acid bacteria. Fermentation. Antioxidant peptides production. Wheat protein hydrolysis. Functional food ingredients.

Resumo

A crescente demanda por alimentos funcionais levou a um interesse em processos de fermentação que aumentam a produção de peptídeos antioxidantes. Este estudo teve como objetivo realizar uma análise bibliométrica de bactérias do ácido láctico (BAL) usadas na fermentação do trigo para produzir peptídeos antioxidantes. Para isso, dados de 2010 a 2023 foram coletados do banco de dados Web of Science®, com foco em publicações relacionadas a BAL, proteínas do trigo e peptídeos antioxidantes. Os resultados da pesquisa foram analisados usando o pacote bibliometrix R, que permitiu um exame aprofundado de tendências de pesquisa, colaborações e estudos influentes. Os resultados indicaram aumento da atividade de pesquisa, com uma taxa média de crescimento anual de 13,18% e contribuições de países como China e Itália. As principais áreas de foco incluíram métodos de fermentação, produção de peptídeos e aplicações de compostos bioativos relacionadas à saúde. As redes de colaboração destacaram a importância de parcerias internacionais no avanço deste campo. Os resultados forneceram insights sobre o desenvolvimento e a aplicação de BAL na ciência dos alimentos, enfatizando o potencial dos peptídeos bioativos produzidos a partir do trigo na promoção da saúde por meio da atividade antioxidante. Este estudo contribui para a compreensão do cenário de pesquisa e do potencial futuro do uso de LAB para produzir ingredientes alimentares funcionais.

Palavras-chave: Bactérias do ácido láctico. Fermentação. Produção de peptídeos antioxidantes. Hidrólise de proteína de trigo. Ingredientes alimentares funcionais.

Graphical Abstract



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Submitted 01 March 2025; Accepted: 11 March 2025; Published: 13 March 2025.

ROYALDATASET

1. Introduction

In carbohydrate fermentation, microorganisms such as lactic acid bacteria (LAB), including *Lactobacillus* species and yeasts like *Saccharomyces cerevisiae* satisfy their nitrogen requirements by utilizing proteins in the fermentation medium. Their proteolytic activity primarily facilitates this process, which hydrolyzes proteins into smaller peptides and free amino acids that can be assimilated for growth and metabolic functions. *Lactobacillus* species, for example, employ cell membrane proteinases to degrade environmental proteins, releasing bioactive peptides and free amino acids essential for their growth and metabolism (Raveschot et al., 2018). Additionally, certain carbohydrate-fermenting bacteria exhibit significant deamination rates, converting amino acids into ammonia as an additional nitrogen source (Bento et al., 2015). This interplay between carbohydrate fermentation and protein utilization supports microbial populations and ensures efficient fermentation processes.

Fermentation enhances protein digestibility and increases the bioavailability of amino acids and bioactive peptides. During fermentation, proteins are broken down into smaller peptides (often under 10 kDa), which may demonstrate many bioactive properties, including antihypertensive, antioxidant, and immunomodulatory activities (Islas-Martínez et al., 2023; Kinayang et al., 2021; Shukla et al., 2023; Tachie et al., 2024; Wei et al., 2021). Fermented soybean curd produces several bioactive peptides that enhance its health advantages (Wei et al., 2021). Likewise, conventional fermented foods, like salted shrimp paste, exhibit differences in ammonia nitrogen levels, which are associated with the degree of protein degradation and the subsequent rise in bioactive chemicals (Pongsetkul et al., 2014). Additionally, the fermentation process can alter the microbial community structure, promoting the growth of beneficial bacteria that further enhance the nutritional profile of the fermented product (Bindelle et al., 2011).

LAB secrete proteolytic enzymes that decompose proteins into more digestible peptides and amino acids, offering health benefits such as antioxidant and anti-inflammatory effects (De Montijo-Prieto et al., 2023; Wang et al., 2022). For instance, the fermentation of soybean protein meal with *Lactobacillus plantarum* has increased protein solubility and enhanced the presence of essential amino acids, improving its nutritional attributes (Amadou et al., 2011). LAB are a diverse group of Gram-positive, non-sporulating, and catalase-negative microorganisms commonly used in the food industry due to their GRAS (Generally Recognized as Safe) status. They contribute to producing various fermented foods such as yogurt, cheese, and vegetables (Hayek & Ibrahim, 2013; Leroy & De Vuyst, 2004). They ferment carbohydrates primarily into lactic acid, contributing to rapid acidification that inhibits spoilage organisms and pathogens, thus enhancing food preservation and safety (Arcales & Alolod, 2018; Nasrollahzadeh et al., 2019; Wu et al., 2011). LAB also produce antimicrobial compounds like bacteriocins and hydrogen peroxide, further extending shelf-life and improving sensory attributes (Leroy & De Vuyst, 2004; Lynch et al., 2018).

Wheat proteins, mainly gluten, gliadins, and glutenins, play an important role in the functional properties of wheat flour in food applications. They provide unique viscoelastic properties that help shape the structure and texture of baked products (Cho et al., 2018; Ramos et al., 2021). Glutenins contribute to dough elasticity and strength through disulfide bond formation, while gliadins impart viscosity and extensibility; the balance between them determines the dough's viscoelastic properties (Barak et al., 2015; Feng et al., 2021; Gojković Cvjetković et al., 2022; Zou et al., 2022).

Wheat is an excellent substrate for LAB fermentation due to its rich carbohydrate content and protein matrix, which can trap gases produced during fermentation, enhancing leavening and texture in products like sourdough bread (Hayek & Ibrahim, 2013; Leroy & De Vuyst, 2004). Fermentation modifies wheat protein structure, improving digestibility and nutritional value while reducing anti-nutritional factors (De Montijo-Prieto et al., 2023; Wang et al., 2022).

Antioxidant peptides, derived from protein hydrolysis during fermentation, can neutralize free radicals and reduce oxidative stress linked to chronic diseases such as cardiovascular disorders, cancer, and neurodegenerative conditions (Tadesse & Emire, 2020; Uno et al., 2020; Zou et al., 2016). LAB releases peptides from milk and corn proteins through enzymatic processes, producing bioactive compounds with health benefits (Ramesh et al., 2012; Xu et al., 2022). Specific amino acids like cysteine, histidine, and proline enhance their antioxidant capacity (Zhang et al., 2020; Zhao et al., 2022). These peptides scavenge reactive oxygen species, chelate metal ions, and modulate cellular antioxidant defenses, contributing to overall health and well-being (Tadesse & Emire, 2020; Uno et al., 2020).

In addition, antioxidant peptides are recognized in the food industry for their roles as natural preservatives and functional ingredients, enhancing the shelf life and nutritional quality of food products (Lorenzo et al., 2018; Nwachukwu & Aluko, 2019; Y. Zhang et al., 2024; Zhu et al., 2022). They are incorporated into functional beverages, dairy, and meat products, offering health benefits and meeting consumer demand for functional foods (Torres-Fuentes et al., 2014; Zaky et al., 2022; H. Zhang et al., 2022). Recent developments in enzymatic hydrolysis and bioinformatics have improved peptide production, increasing their antioxidant capacity and enabling their use in health-promoting foods and dietary supplements (López-Pedrouso et al., 2022; Ningrum et al., 2023).

Bibliometric analysis is a quantitative method to evaluate scientific research output and impact. It helps identify trends, collaboration networks, and developments in specific fields (Farias et al., 2022; Ribeiro et al., 2023; O. L. Zhang et al., 2022). Bibliometric analysis can reveal growth areas, influential studies, and research gaps in target subjects like fermentation (Chen et al., 2020) and antioxidant peptide production (Xu et al., 2022; Zhu et al., 2023), guiding future research directions.

This study aims to perform a bibliometric analysis to identify and assess LAB's role in wheat fermentation, focusing on producing antioxidant peptides. The study also analyzes research trends and highlights key findings to enhance the understanding of their potential applications in food science and health.

2. Methodology

A bibliometric analysis utilized the advanced Web of Science® (WoS) search feature, employing a meticulously designed logical search string to identify pertinent material. The employed search string was ‘TS = (("lactic fermentation" OR "lactic acid bacteria" OR "LAB" OR "fermentation") AND ("wheat protein" OR "wheat") AND ("peptide*") AND ("antioxidant*"))’. This logical function was designed to identify studies centered on lactic fermentation and the application of lactic acid bacteria in producing antioxidant peptides from wheat proteins. The search string aimed at pertinent literature in English by integrating phrases associated with lactic fermentation, lactic acid bacteria, and wheat proteins, emphasizing peptides and their antioxidant properties.

The search was narrowed by omitting document types, including review articles and early-access publications. The publishing years were filtered to encompass publications from 2010 to 2023, offering a concentrated perspective on research trends. This methodology yielded a dataset for the subsequent bibliometric analysis (García-Curiel et al., 2024; Pérez-Flores et al., 2024). The search results were exported as a single BibTeX file (savedrecs.bib) to enable processing and analysis. This file included authors, titles, abstracts, keywords, affiliations, citations, and additional pertinent metadata.

A bibliometric analysis was conducted on a computer operating "elementary OS 7.1 Horus" (Linux 6.8.0-40-generic). The study utilized R version 4.1.2 (2021-11-01) "Bird Hippie", in conjunction with the 'bibliometrix' package version 4.1.4 and its graphical interface, 'biblioshiny'. The investigation utilized Rstudio® 2024.04.2+764 "Chocolate Cosmos" as the integrated development environment. The requisite libraries were imported using the command 'library(bibliometrix)', and the graphical interface was launched with 'biblioshiny'.

3. Results and Discussion

3.1. Scientific production from 2010 to 2023 timespan

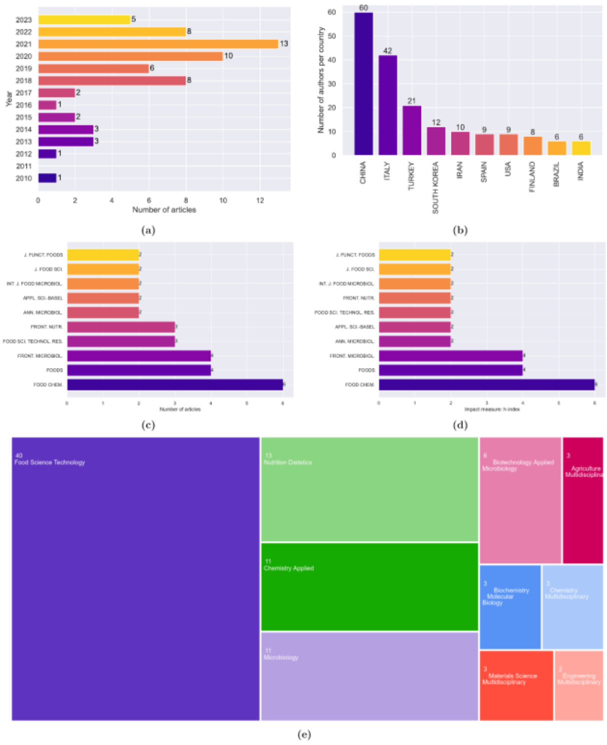
The bibliometric analysis presented in **Table 1** provided an overview of various aspects of the research on LAB in wheat fermentation from 2010 to 2023. During this period, 42 sources, including journals and books, were identified, contributing to 63 documents. The annual growth rate of publications in this field was 13.18%, indicating a significant increase in research activity. The documents had an average age of 4.87 years, reflecting the relatively recent nature of the studies. Each document received an average of 25.84 citations, indicating the significance and pertinence of the research within the scientific community.

Regarding the content of these documents, 298 Keywords Plus and 255 Author's Keywords were identified, suggesting a wide range of research topics and terminologies associated with the field. The authorship data revealed that 288 authors contributed to the publications, with no single-authored documents indicating a solid collaborative effort among researchers. Collaboration was further highlighted by an average of 5.11 co-authors per document, underscoring the team-based approach prevalent in this research area. Additionally, 25.4% of the documents involved international co-authorships, reflecting global collaboration. All 63 documents in the dataset were classified as articles, reaffirming the scholarly nature of the contributions.

Table 1 Bibliometric overview of research on lactic acid bacteria in wheat fermentation on the 2010-2023 timespan.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2010-2023
Sources (Journals, Books, etc)	42
Documents	63
Annual Growth Rate (%)	13.18
Document Average Age	4.87
Average citations per doc	25.84
DOCUMENT CONTENTS	
Keywords Plus (ID)	298
Author's Keywords (DE)	255
AUTHORS	
Authors	288
Authors of single-authored docs	0
AUTHORS COLLABORATION	
Single-authored docs	0
Co-Authors per Doc	5.11
International co-authorships (%)	25.4
DOCUMENT TYPES	
Article	63

Fig. 1 presents a graphic summary of the principal trends and attributes of research concerning LAB in wheat fermentation from 2010 to 2023. It encompasses several elements, including the yearly publication distribution, the geographical distribution of contributing authors, the primary scientific sources and their contributions, the h-index values of journals, and the distribution of research across various Web of Science® categories. These subfigures depict the area's expansion, global cooperation, distribution mechanisms, influence, and multidisciplinary emphasis.



(a) (b) (c) (d) (e)

Fig. 1 Publications and key metrics of lactic acid bacteria in wheat fermentation research (2010-2023). (a) Number of articles published per year (2010-2023). (b) Distribution of authors by country. (c) Number of articles published by the journal. (d) Comparison of h-index values for journals contributing to research. (e) Distribution of research across Web of Science® categories.

Fig. 1a depicts the annual distribution of papers concerning LAB in wheat fermentation from 2010 to 2023. The publication commenced with one paper in 2010, with no subsequent publications in 2011. The quantity of articles progressively escalated, starting with 1 article in 2012 and increasing to 3 articles in 2013 and 2014. A minor decrease was observed in 2015 and 2016, with 2 and 1 articles published, respectively. From 2017 onward, there was an increase in research production, with 8 articles published in 2018 and 6 in 2019. The increasing trajectory persisted, culminating in a peak of 13 articles in 2021, followed by a modest decline to 8 articles in 2022 and 5 in 2023. This overarching pattern signifies a growing scholarly interest, especially in the early 2020s.

Fig. 1b illustrates the geographical distribution of authors engaged in research on LAB in the fermentation of wheat. The data indicated that China had the preeminent number of contributing authors, with 60 writers signifying a dominant influence in this research domain. Italy ranked second with 42 authors. Turkey provided 21 authors, ranking it as the third most active nation. South Korea, Iran, and Spain had 12, 10, and 9 authors, respectively, indicating moderate participation. The United States also had nine writers, suggesting a similar contribution level to Spain's. Finland, Brazil, and India had 6 to 8 authors, signifying modest participation. This distribution indicates that research in this domain is concentrated in many significant nations, with China and Italy as the foremost contributors.

Fig. 1c illustrates the distribution of publications about LAB and wheat fermentation published in diverse scientific sources. The journal Food Chemistry was recognized as the primary source, publishing 6 articles, underscoring its central role in spreading research on this subject. Foods and Frontiers in Microbiology published 4 articles indicating their importance in this research domain. Food Science and Technology Research and Frontiers in Nutrition published three publications emphasizing their moderate engagement. Additional journals, including Annals of Microbiology, Applied Sciences – Basel, International Journal of Food Microbiology, Journal of Food Science, and Journal of Functional Foods, each published 2 papers, indicating a wider yet less regular distribution of publications. This pattern indicates that while specific journals dominate in publishing this research, diverse sources support disseminating findings in this field.

Fig. 1d compares the h-index values of diverse scientific journals researching BAL and wheat fermentation. Food Chemistry has the greatest h-index of 6, signifying its publication of highly cited publications in this domain, underscoring its prominence as a primary source. Foods and Frontiers in Microbiology possessed an h-index of 4, indicating a notable effect despite a lower volume of papers than Food Chemistry. Multiple journals, such as Annals of Microbiology, Applied Sciences – Basel, Food Science and Technology Research, Frontiers in Nutrition, International Journal of Food Microbiology, Journal of Food Science, and Journal of Functional Foods, each possessed an h-index of 2, signifying that their contributions, although existent, were cited infrequently. The distribution of h-index values indicates that although many journals regularly disseminate highly cited research, several sources contribute to the broader field with a very modest influence.

Fig. 1e, depicted as a Treemap chart, demonstrates the allocation of research among diverse Web of Science® categories about LAB and wheat fermentation. The largest category was Food Science Technology, which accounted for 61.54% of the 65 records, indicating that most research in this field is focused on food science. Nutrition Dietetics represented 20.00% of the records, showing the importance of nutritional aspects in the studies. Both Chemistry Applied and Microbiology were represented by 16.92% of the records, reflecting a significant focus on chemical and microbiological approaches within the research. Other categories, such as Biotechnology Applied Microbiology (9.23%) and several smaller categories like Agriculture Multidisciplinary, Biochemistry Molecular Biology, Chemistry Multidisciplinary, and Materials Science Multidisciplinary (each contributing 4.62%), indicate a broad interdisciplinary nature of the research. A range of categories contributed smaller portions (each 1.54% to 3.08%), including fields such as Environmental Sciences, Nanotechnology, Plant Sciences, and Green Sustainable Science Technology. This suggests that while food science dominates, there is also a diverse interest in related scientific disciplines. This wide distribution highlights the interdisciplinary nature of research in this area.

The top 10 most-cited papers related to LAB in wheat fermentation were analyzed in **Table 2**, highlighting their total citations, yearly citation rates, and normalized citation counts. The paper by Coda et al. (2012) in Applied and Environmental Microbiology had the highest total citation count, with 156 citations, averaging 12 per year. However, the paper by Verni et al. (2020) in Frontiers in Microbiology achieved the highest normalized citation count (2.68) and the highest yearly citation rate of 16.6, indicating a more recent but highly impactful contribution. Nionelli et al. (2014) and Nilsson et al. (2013) also had notable normalized citation counts of 1.84 and 1.85, respectively, suggesting sustained relevance in the field. Babini et al. (2017) and Liu et al. (2017), published in Food Chemistry and Food Bioscience, received comparable citation rates of around 10 per year, reflecting their importance. The overall trends show that while older papers accumulate higher total citations, newer papers receive citations faster, highlighting the evolving and expanding interest in the field.

Table 2 Top 10 on lactic acid bacteria and wheat fermentation: Citation metrics overview.

Title	Journal	Total Citations (TC)	TC per Year	Normalized TC	Reference
Selected lactic acid bacteria synthesize antioxidant peptides during sourdough fermentation of cereal flours	Applied and Environmental Microbiology	156	12	1	Coda et al. (2012)
Manufacture and characterization of a yogurt-like beverage made with oat flakes fermented by selected lactic acid bacteria	International Journal of Food Microbiology	134	12.18	1.84	Luana et al. (2014)
Effects of a brown beans evening meal on metabolic risk markers and appetite regulating hormones at a subsequent standardized breakfast: A randomized cross-over study	PLoS ONE	97	8.08	1.85	Nilsson et al. (2013)
Bioprocessing of brewers' spent grain enhances its antioxidant activity: Characterization of phenolic compounds and bioactive peptides	Frontiers in Microbiology	83	16.6	2.68	Verni et al. (2020)
LC-ESI-QTOF-MS identification of novel antioxidant peptides obtained by enzymatic and microbial hydrolysis of vegetable proteins	Food Chemistry	83	10.38	1.02	Babini et al. (2017)
Effect of fermentation on the peptide content, phenolics and antioxidant activity of defatted wheat germ	Food Bioscience	80	10	0.98	Liu et al. (2017)
Effect of bioprocessing and particle size on the nutritional properties of wheat bran fractions	Innovative Food Science & Emerging Technologies	61	5.55	0.84	Coda et al. (2014)
In vitro investigation of bioactivities of solid-state fermented lupin, quinoa and wheat using *Lactobacillus* spp.	Food Chemistry	54	9	2.27	Ayyash et al. (2019)
Preparation and evaluation of antioxidant activities of peptides obtained from defatted wheat germ by fermentation	Journal of Food Science and Technology-Mysore	48	4	0.92	Niu et al., (2013)

On the other hand, **Table 3** compares different studies focusing on the fermentation of various substrates, emphasizing the microorganisms utilized and their impact on antioxidant activity and other health-enhancing attributes. The variety of substrates, including cereal flours, oat flakes, brewers' leftover grain, and defatted wheat germ, illustrates the adaptability of fermentation in improving the bioactivity and functional properties of these materials.

Table 3 Comparative analysis of fermentation studies on various food substrates and their bioactive properties based on the top 10 best-cited articles.

Fermentation substrate	Microorganism	Key findings	Reference
Cereal flours	*Lactobacillus* spp.	Identified 25 new antioxidant peptides during sourdough fermentation, suggesting synergistic antioxidant activity.	Coda et al. (2012)
Oat flakes flour (OFF)	*L. plantarum* LP09	Developed a yogurt-like beverage with 25% OFF, achieving optimal texture and sensory qualities.	Luana et al. (2014)
Brown beans	Non-applicable	Demonstrated improved metabolic risk markers and increased satiety hormones after brown bean consumption.	Nilsson et al. (2013)
Brewers' spent grain (BSG)	*L. plantarum*	Enhanced antioxidant activity and dietary fiber content, promoting sustainable use of BSG in food products.	Verni et al. (2020)
Cereal and legume proteins	*Lactobacillus* spp. and enzymes	Identified antioxidant peptides from hydrolyzed proteins of KAMUT® wheat, emmer, pea, and lupine.	Babini et al. (2017)
Defatted wheat germ (DWG)	*Bacillus subtilis*	Increased phenolic and peptide content, enhancing antioxidant activity during fermentation.	Liu et al. (2017)
Wheat bran	*Lactobacillus brevis* E95612 and *Kazachstania exigua* C81116	Improved the bioaccessibility of health-promoting compounds by bioprocessing, enhancing nutritional value.	Coda et al. (2014)
Whole grains (lupin, quinoa, wheat)	*Lactobacillus* spp.	Increased antioxidant activities depending on the probiotic strain highlight fermentation's nutritional benefits.	Ayyash et al. (2019)
Defatted wheat germ	*Bacillus subtilis* B1	Optimized fermentation conditions for increased yield of antioxidant peptides using a Box-Behnken design.	Niu et al. (2013)
Lupin, quinoa, wheat	*Bifidobacterium* spp.	Enhanced cytotoxicity, antihypertensive, antidiabetic, and antioxidant activities through fermentation.	Ayyash et al. (2018)

Sourdough fermentation of cereal flours by selected LAB produced 25 novel antioxidant peptides, suggesting a synergistic effect that contributes significantly to antioxidant activity, thus enhancing the nutritional value of fermented cereal products (Coda et al., 2012). This aligns with identifying and maximizing health-promoting compounds in food. Developing a yogurt-like beverage using oat flakes flour (OFF) fermented with LAB is an example of how fermentation can improve sensory and nutritional properties. An OFF concentration of 25% produced the most desirable texture and flavor, balancing liquidity and consistency (Luana et al., 2014). This adds value to oat products and addresses the consumer demand for non-dairy functional beverages.

The potential of fermentation to transform food industry by-products into valuable ingredients is illustrated by the bioprocessing of brewers' spent grains (BSG) with LAB, which enhances antioxidant activity and dietary fiber content (Verni et al., 2020). Similar trends were observed with defatted wheat germ fermented by *Bacillus subtilis*, where phenolic compound release and antioxidant properties were enhanced, demonstrating the feasibility of converting by-products into functional foods with improved health benefits (Liu et al., 2017).

Fermentation of whole grains (lupin, quinoa, wheat) using *Lactobacillus* spp. enhanced antioxidant activities, with the extent of improvement varying according to the strain used, highlighting the importance of strain selection in optimizing health benefits (Ayyash et al., 2018). Additionally, the effective optimization of fermentation conditions for defatted wheat germ peptides using a Box-Behnken design maximized yield, showing the role of experimental optimization in enhancing production efficiency (Niu et al., 2013).

The identification of antioxidant peptides in multiple studies supports the role of microbial hydrolysis in generating compounds with health-promoting properties (Babini et al., 2017; Coda et al., 2012). Moreover, the studies involving fermentation with *Bacillus subtilis* and *Bifidobacterium* species underline the significance of microorganism selection in achieving specific functional improvements, such as enhanced antioxidant, antihypertensive, and antidiabetic activities (Ayyash et al., 2018; Liu et al., 2017). The consistent improvements in nutritional and sensory properties across these studies show that fermentation is a promising technique for valorizing by-products and developing novel, health-oriented food products.

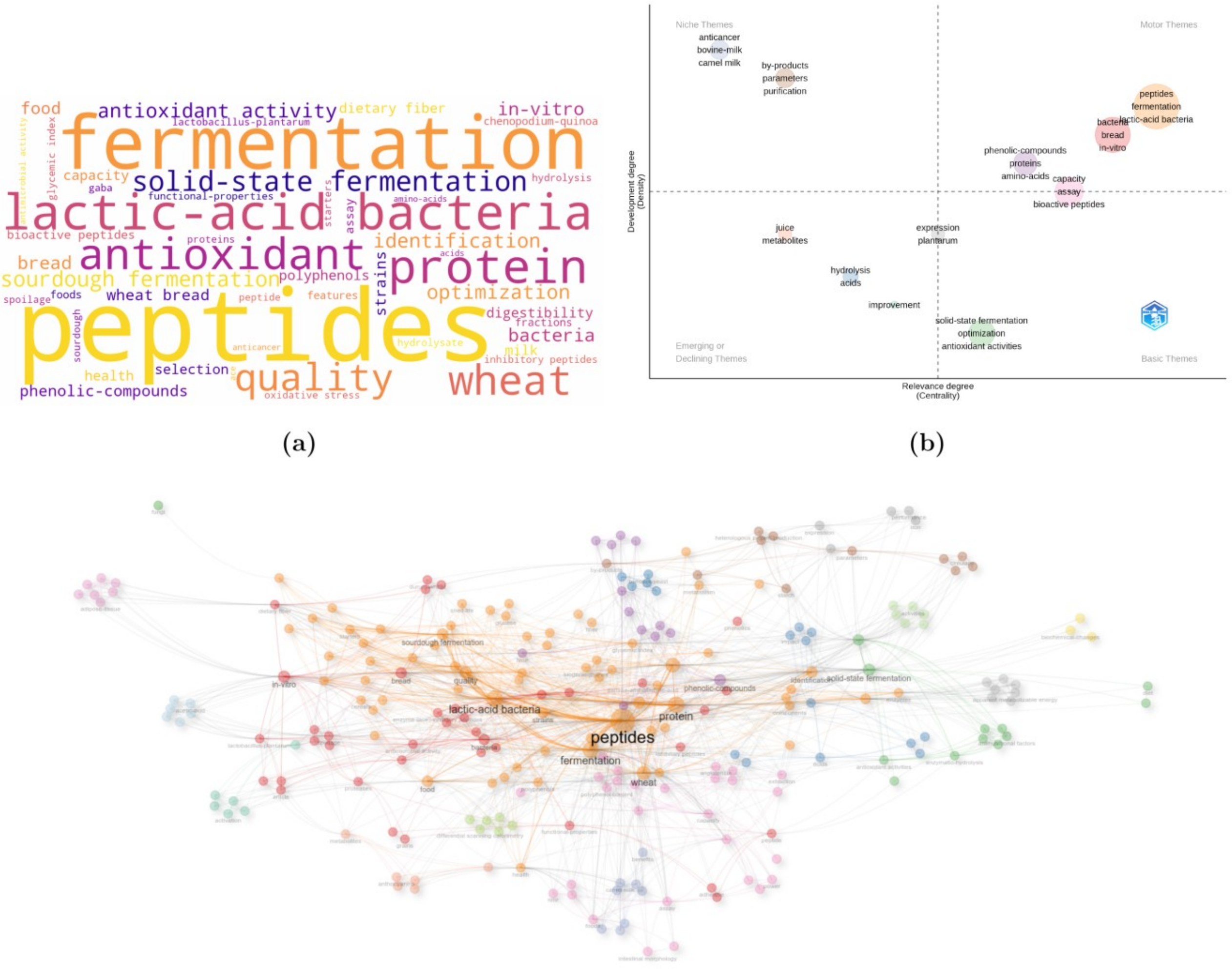
3.2. Authors' keywords analysis

Fig. 2 presents the authors' keyword analysis results, providing an overview of the research landscape related to LAB and wheat fermentation. It showcases the focus areas and interrelationships between topics.

Fig. 2a, the word cloud generated from the Authors' keywords was analyzed to illustrate the most frequently occurring terms in research related to LAB and wheat fermentation. The term "peptides" appeared most frequently, with 27 co-occurrences, indicating the central focus on peptide production in this field. "Fermentation" and "lactic acid bacteria" appeared 13 times, reflecting their critical roles in transforming wheat proteins. "Protein" (12 occurrences) and "antioxidant" (10 occurrences) were also prominent, highlighting the interest in the functional properties of peptides, particularly their antioxidant activity.

Other notable terms include "wheat" (9 occurrences) and fermentation methods such as "solid-state fermentation" and "sourdough fermentation" (both with 8 occurrences), suggesting diverse approaches to peptide production. Terms like "antioxidant activity" (7 occurrences), "optimization" (7 occurrences), and "identification" (7 occurrences) emphasize the focus on improving the efficiency and characterization of the antioxidant peptides. Keywords such as "quality", "bacteria", and "bread" (6 occurrences each) highlight the interest in the practical applications of fermentation, particularly in bread products.

Additionally, "phenolic compounds", "dietary fiber", and "digestibility" (4 occurrences each) suggest a focus on health-related aspects of fermented products. The co-occurrence of these terms indicates a research trend that integrates fermentation techniques, peptide bioactivity, and health benefits, particularly in the context of antioxidant properties and food quality.



(a) (b)

(c)

Fig. 2 Keyword analysis and thematic mapping of lactic acid bacteria and wheat fermentation research. (a) Word cloud showing the 50 most frequent terms used in the field. (b) Thematic map categorizes research themes into quadrants based on development and relevance. (c) Network visualization of frequent terms, organized into clusters representing central themes and their interconnections.

Fig. 2b represents a thematic map illustrating the co-occurrence of LAB and wheat fermentation research terms, categorized into four quadrants based on their relevance (centrality) and development (density). The upper-right quadrant represents Motor Themes, which are well-developed and significant to the research field. Here, the terms “peptides”, “fermentation”, and “lactic acid bacteria” are prominent, indicating that these concepts are central and actively studied within this research domain. Additionally, “bread” and “in-vitro” experiments are closely linked, reflecting practical applications of fermentation in food science.

In the lower-right quadrant, Basic Themes are foundational but less developed. Terms such as “solid-state fermentation”, “optimization”, and “antioxidant activities” suggest that these topics may require further exploration and refinement to increase their impact. The upper-left quadrant, Niche Themes, features topics like “anticancer”, “bovine-milk”, and “camel milk”. These topics are specialized and less connected to the core research but are highly developed in their respective niches. They may reflect emerging interests that could influence future studies.

In the lower-left quadrant, Emerging or Declining Themes are represented by terms like “juice”, “metabolites”, and “hydrolysis”, suggesting that these topics are either gaining traction or diminishing in relevance. This thematic map highlights the centrality and development of critical concepts, offering insights into well-established and emerging research areas.

The network map in **Fig. 2c** highlights the interconnected clusters that define the research landscape of lactic acid bacteria and wheat fermentation. Each cluster represents a thematic group of frequently co-occurring research terms, showing how different aspects of the field are interrelated. The largest cluster is “Cluster 5: Peptides”, which holds the highest centrality (btw_centrality = 5797.88) and density (85.03). This cluster revolves around core terms like “peptides”, “fermentation”, “lactic acid bacteria”, and “antioxidant”, which play important roles in the production of bioactive compounds in fermented foods. The cluster’s centrality suggests its significant influence in the field, linking various research areas, including the potential health benefits of peptides and their applications in food science.

"Cluster 1: Bacteria" is another highly significant cluster (btw_centrality = 740.02). It focuses on practical applications, with terms like "bread", "in-vitro", "dietary fiber", and "milk". This cluster shows the relevance of LAB in improving food quality, particularly in baked goods and dairy products. The emphasis on "in-vitro" suggests experimental studies that explore the interaction between LAB and food substrates, further underscoring the practical applications of these microbes in enhancing nutritional value.

Additionally, "Cluster 3: Solid-state Fermentation" (btw_centrality = 1461.97) centers on improving fermentation methods, particularly optimizing solid-state fermentation to enhance antioxidant activities. This cluster highlights research aimed at refining fermentation techniques, focusing on increasing efficiency and bioactive compound production, which is essential for commercial and large-scale food applications. The presence of terms like "optimization" and "enzymatic hydrolysis" further reinforces the importance of fine-tuning fermentation processes.

Smaller clusters like "Cluster 4: Phenolic-compounds" (btw_centrality = 1269.75) reveal the biochemical interactions within fermentation, focusing on compounds like proteins and amino acids and their antioxidant properties. This cluster connects fermentation to nutritional science, particularly regarding the health benefits of phenolic compounds in fermented foods. Including "digestibility" suggests that this research area is concerned with improving how fermented products are broken down and absorbed by the body, making them more nutritionally valuable.

The "Cluster 6: By-products" (btw_centrality = 400.43) takes a different approach by focusing on sustainability, explicitly optimizing and purifying by-products generated during fermentation. This cluster's high density (87.50) indicates a mature research focus aimed at reducing waste and maximizing the use of fermentation by-products, contributing to sustainability efforts in food production. "Cluster 2: Hydrolysis" (btw_centrality = 230.14) and "Cluster 7: Capacity" (btw_centrality = 523.24) represent specialized biochemical processes within the broader fermentation context. Cluster 2 focuses on the enzymatic breakdown of proteins, a necessary process in fermentation. Cluster 7 explores the capacity of bioactive compounds, particularly bioactive peptides, to enhance the functional properties of foods. Both clusters underline the detailed biochemical research supporting fermented foods' production and improvement.

Smaller, more specialized clusters such as "Cluster 8: Expression" and "Cluster 9: Improvement" show focused research areas. The expression cluster investigates the genetic mechanisms behind bacterial activity in fermentation, particularly in *Lactobacillus plantarum*. Meanwhile, the improvement cluster focuses on enhancing food formulations through fermentation, emphasizing improving fermented products' sensory and nutritional attributes. "Cluster 10: Juice" (btw_centrality = 125.04) focuses on fermented beverages, particularly the metabolites produced during juice fermentation. These beverages are increasingly gaining attention as functional foods, suggesting a growing interest in their health benefits and sensory properties.

Finally, "Cluster 11: Anticancer" (btw_centrality = 59.74), although isolated from the core clusters, is highly developed (density = 125) and focuses on niche research areas, such as the anticancer potential of fermented dairy products like camel and bovine milk. This cluster, though peripheral, could have significant implications for health-related research, especially as the bioactive properties of fermented foods continue to be explored for their medicinal benefits.

Therefore, **Fig. 2** thoroughly examines the existing research landscape concerning lactic acid bacteria and wheat fermentation. The keyword analysis, thematic map, and network map collectively emphasize the primary focus on peptide formation, its bioactive qualities, and the essential importance of fermentation processes. The way that well-established topics like "peptides" and "fermentation" interact with more recent subjects like "optimization" and "anticancer" suggests that the discipline is dynamic and constantly changing. This research landscape indicates a heightened focus on the practical uses of fermentation in food production and the investigation of novel health advantages, therefore enhancing the potential of fermented products in functional food development.

3.3. Factorial analysis

Fig. 3 is a Conceptual Structure Map created using the Multiple Correspondence Analysis (MCA) method. It visually represents how various research terms are related to LAB and wheat fermentation. The figure is divided into two dimensions, with Dim 1 explaining 27.46% of the variance and Dim 2 accounting for 17.94%, capturing significant patterns in the dataset.

In the upper-left quadrant, terms like "camel milk", "bovine milk", "anticancer", and "cereal grains" are clustered together, indicating that these topics are more niche areas of study within the overall research domain. These terms, particularly "camel milk" and "bovine milk", suggest specialized interest in dairy products and their bioactive compounds, possibly focusing on health-related properties such as anticancer activities. The high position in Dim 2 indicates a more robust development in terms of research volume for these topics, though they are less central to the field (lower Dim 1 values).

In contrast, the lower-central portion of the map includes more central research terms such as "fermentation", "inhibitory peptides", and "cheese". These terms indicate more foundational aspects of fermentation research, where studies focus on peptides' inhibitory activities and traditional fermented products like cheese. The proximity of these terms in the map suggests a connection between peptide production and food applications, with moderate variability in the research direction.

Moving to the right-hand side, the terms "selection", "bioavailability", "starters", and "exploitation" form a tight cluster that suggests an advanced level of research related to fermentation starter cultures and their selection for optimized bioavailability in food products. The position along the Dim 1 axis highlights these topics' central role in the research domain, making them highly relevant for practical food science and technology applications.

In the lower-right quadrant, terms like "sourdough", "wheat bread", and "dietary fiber" appear. These terms emphasize the importance of fermented bakery products, particularly enhancing health benefits through dietary fiber. The centrality of these topics in the fermentation research landscape is demonstrated by their relatively high positions in Dim 1, indicating they are well-studied areas with broad implications for nutrition and food technology.

Furthermore, **Fig. 3** effectively illustrates the research landscape of LAB and wheat fermentation, showing clusters of closely related terms that reflect both niche areas (e.g., dairy and anticancer studies) and core themes (e.g., fermentation, bioavailability, and bakery products). The distribution of these terms across Dim 1 and Dim 2 reflects the variability in the relevance and development of these research topics, providing insights into how different research foci are interconnected within the field.

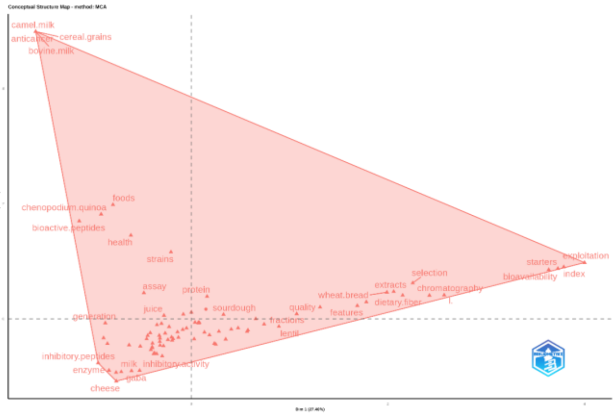


Fig. 3 Conceptual structure map of research terms in lactic acid bacteria and wheat fermentation using multiple correspondence analysis (MCA), highlighting key themes and niche areas.

3.4. Future perspectives and challenges

3.4.1. Optimization of fermentation processes

Optimizing solid-state fermentation (SSF) and other techniques to enhance bioactive peptide and antioxidant compound production depends on factors like temperature, pH, and starter culture selection, which directly influence microbial activity and metabolite production. Temperature and pH impact yields. Feruloyl esterase-producing strains show optimal activity around 30 °C and pH 7.0–8.0, facilitating the release of ferulic acid (Y. Zhang et al., 2022). Controlled adjustments in a two-stage fermentation prevent substrate inhibition, enhancing metabolites like γ-aminobutyric acid (Yang et al., 2016). Maintaining optimal conditions is thus necessary for maximizing metabolite production.

Starter culture selection also influences fermentation efficiency and product quality. Indigenous LAB improve cocoa bean fermentation by promoting favorable microbial populations that enhance flavor and aroma (Kresnowati & Febriami, 2015; Marwati et al., 2024). Combining different cultures can create synergistic effects; for example, *Lactobacillus plantarum* in fermented goat's milk inhibits pathogens while boosting antimicrobial compounds (Fayemi & Buys, 2017). Tailoring the starter allows for optimizing bioactive compound production, like antioxidant peptides.

Incorporating sustainable practices addresses optimization challenges. Using locally sourced cultures and substrates minimizes the carbon footprint. Bioprocess control strategies like real-time monitoring maintain optimal microbial growth, enhance yield, and reduce waste (Abunde, Asiedu & Addo, 2019). Integrating non-thermal microbial inactivation techniques may improve culture effectiveness while promoting sustainability (Kim et al., 2024).

Optimizing SSF and fermentation techniques for bioactive peptides and antioxidant compounds involve precise control of temperature and pH, strategic starter culture selection, and sustainable practices. Addressing these factors enhances fermentation efficiency and bioactive compound production.

3.4.2. Exploring novel substrates and by-products

Incorporating underutilized substrates like cereal grains, camel milk, and food industry by-products into large-scale fermentation enhances bioactive compound production. It promotes sustainability through optimized conditions and cost-effective methods. Cereal grains, rich in carbohydrates, serve as cost-effective fermentation substrates. Fermenting barley and wheat increases nutrient bioavailability and produces bioactive peptides. For example, fermenting barley with LAB boosts antioxidant properties (Alhaj et al., 2018). Optimizing parameters like temperature and pH further enhances bioactive compound production (Bragason et al., 2020).

Camel milk, abundant in immunoglobulins and unsaturated fatty acids, supports beneficial microorganism growth during fermentation (Nozari et al., 2022). Spontaneous fermentation utilizes its natural microbiota, reducing the need for expensive starter cultures and enhancing unique flavors and bioactive compounds (Tak et al., 2018). Fermented camel milk also exhibits antimicrobial properties beneficial for food preservation (Akhmetsadykova et al., 2014). Food industry by-products like whey and spent grains are nutrient-rich substrates for fermentation. Fermenting whey into dairy products reduces waste while enhancing its value (Zibaee et al., 2015). Fermented spent grains yield bioactive peptides with antioxidant properties, turning waste into valuable resources (Moslehishad et al., 2013).

Cost-effective integration strategies include optimizing fermentation conditions, using mixed microbial cultures to utilize diverse substrates efficiently (Althnaian, Albokhadaim & El-Bahr, 2013), employing continuous fermentation systems for constant input and output (Abera et al., 2016), and adding enzymes to break down complex carbohydrates (Ganzorig, Urashima & Fukuda, 2020). Incorporating these underutilized substrates into large-scale fermentation enhances bioactive compound production and sustainability. By optimizing conditions and employing cost-effective strategies, efficient and economically viable processes benefit both producers and consumers.

3.4.3. Health-related applications

Expanding research on the health benefits of bioactive peptides—anticancer, antioxidant, and antimicrobial activities—requires a comprehensive approach addressing scientific and practical challenges, especially in proving their bioavailability and efficacy in human clinical trials. Well-designed *in vitro* and *in vivo* studies are necessary. While *in vitro* models offer preliminary insights, they often fail to predict human responses; thus, *in vivo* studies, including animal models and human trials, are necessary. For example, food-derived bioactive peptides have demonstrated significant antioxidant and antimicrobial activities in animal models, paving the way for human trials (Bhardwaj & Singh, 2016; Zaky et al., 2022).

Bioavailability is also challenging; factors like gastrointestinal stability, absorption rates, and tissue targeting affect effectiveness. Research should focus on novel delivery systems like nanocarriers and encapsulation techniques to enhance strength and absorption during digestion, improving transport across the intestinal barrier (Amigo & Hernández-Ledesma, 2020; X. Zhang et al., 2022).

Understanding the mechanisms of action is necessary. Studying interactions with cellular pathways provides insights into their anticancer, antioxidant, and antimicrobial properties. For instance, neuroprotective peptides modulate redox systems, which are determinants in preventing oxidative stress-related diseases and supporting their therapeutic potential (Q. Zhang et al., 2024).

Standardizing peptide extraction, characterization, and bioactivity assessment methods determines credible research. Regulatory bodies require robust evidence of efficacy and safety before approving health claims. Collaborating with regulatory agencies can help develop guidelines for clinical applications, addressing challenges like variability in absorption and gastrointestinal digestibility (Chakrabarti, Guha & Majumder, 2018; Rutherfurd-Markwick, 2012).

Well-structured clinical trials allow for the proven efficacy of these treatments in humans. Trials should include diverse populations and use biomarkers for specific health outcomes. Integrating dietary interventions rich in bioactive peptides with lifestyle modifications could enhance outcomes (Amigo & Hernández-Ledesma, 2020; Bouglé & Bouhallab, 2017). Raising public awareness about the health benefits of bioactive peptides can boost research interest and investment. Educating consumers on the potential benefits of foods rich in bioactive peptides could drive demand and encourage further exploration (Zaky et al., 2022).

To advance bioactive peptide research, rigorous studies, innovative delivery methods, mechanistic insights, standardization, well-structured clinical trials, and public education are required. Tackling these factors can strengthen the evidence for peptide efficacy and encourage their inclusion in health-focused dietary strategies.

3.4.4. Sustainability in fermentation

Developing energy-efficient, scalable fermentation processes that use renewable resources and minimize waste requires innovative strategies. These approaches aim to optimize resource utilization, enhance efficiency, and integrate sustainable practices. Renewable resources like agricultural by-products and microalgal biomass reduce waste and improve sustainability. Fermenting microalgal biomass can produce nutraceuticals and bioactive compounds, adding value to waste materials (Garofalo et al., 2022). Food industry by-products like whey and spent grains are cost-effective substrates, minimizing environmental impact (Hughes et al., 2014).

Scaling fermentation can be achieved through energy-efficient technologies. For example, dark fermentation utilizes organic waste to produce biohydrogen more efficiently than traditional methods (Magama, Chiyanzu & Mulopo, 2021), reducing dependence on fossil fuels and improving waste management. Optimizing conditions like temperature and pH leads to higher yields with lower energy inputs; using hot-compressed water, for instance, enhances peptide release while lowering energy consumption (Ishikawa et al., 2023).

Integrating fermentation into a biorefinery maximizes resource utilization and minimizes waste. Coupling biochemical and thermochemical processes converts agricultural residues into biofuels, biochemicals, and energy, promoting a circular economy (Hughes et al., 2014). Advanced monitoring and control systems optimize fermentation by providing real-time data, allowing dynamic adjustments for optimal performance and energy efficiency (Wang et al., 2024). Big data and AI-driven predictive modeling further improve resource management and process optimization (Neethirajan, 2024).

Collaboration among academia, industry, and policymakers drives innovation in sustainable fermentation. Sharing best practices and technological advances facilitates adopting energy-efficient processes (Rachwał & Gustaw, 2024). Engaging local communities incorporates traditional knowledge, enhancing sustainability (Mutlu Sirakova, 2023). Lifecycle assessments (LCA) identify opportunities to reduce energy use and waste. Evaluating the environmental impact of fermentation pathways enables informed decisions to improve sustainability (Tymensen, Beauchemin & McAllister, 2012). Clear sustainability metrics guide the development of energy-efficient processes, aligning with global goals (Ballet et al., 2023).

Overcoming the challenge of creating energy-efficient, scalable fermentation processes demands a comprehensive approach that integrates renewable resources, advanced technologies, and collaboration. Concentrating on these strategies can establish sustainable practices, reduce waste, and contribute to a circular economy.

3.4.5. Personalized nutrition and fermented products

Personalized nutrition through fermented foods tailored to individual health needs is an expanding research area. Using probiotics and bioactive compounds from fermentation, these foods can target specific health outcomes like digestive health, immune function, and metabolic diseases. They may improve gut microbiota composition, which is essential for digestive health (Ibrahim et al., 2023). Specific probiotic strains such as *Lactobacillus* and *Bifidobacterium* have been shown to alleviate irritable bowel syndrome symptoms (Hasan et al., 2014). Fermented foods like natto may enhance immune function by increasing natural killer cell activity (Kobayashi et al., 2013).

Fermented products can also address metabolic diseases. For example, fermented brown rice has demonstrated anti-obesity and antioxidative effects, making it promising for managing weight and metabolic health (Barathikannan et al., 2023). Fermentation enhances nutrient bioavailability and reduces anti-nutritional factors, benefiting those with dietary restrictions or health conditions (Akanni & Adebo, 2024). Diverse microbial communities in fermentation produce unique metabolites targeting specific health outcomes. Fermenting soybeans with *Bacillus subtilis* improves nutritional quality and enzyme activity, enriching them with bioactive compounds (Bi et al., 2015). This microbial diversity allows for creating fermented foods that cater to individual needs.

Scaling up customizable fermented products requires technological advancements. Precision fermentation enables targeted manipulation of microbial strains and conditions to produce specific bioactive compounds (Mandhania et al., 2019). Microbiome analysis helps identify individual gut microbiota variations, allowing producers to develop personalized fermented foods tailored to unique profiles (Gille et al., 2018). Innovative fermentation systems with sensors and data analytics can optimize conditions and ensure product consistency (Neethirajan, 2024). Consumer engagement platforms, such as mobile applications, could enable individuals to input their health data and receive personalized recommendations (Ballet et al., 2023).

Regulatory frameworks must adapt to ensure safety and efficacy as demand for personalized fermented foods grows. Clear guidelines for production and labeling are necessary to maintain consumer trust and compliance with health regulations (C. Borresen et al., 2012). Standardizing the assessment of health claims related to fermented foods is essential for validating benefits and ensuring regulatory adherence (Ibrahim et al., 2023).

Personalized nutrition through fermented foods holds the potential to address health needs such as digestive health, immune function, and metabolic diseases. Advances in precision fermentation, microbiome analysis, intelligent systems, and consumer engagement platforms are essential for making customizable products widely accessible. Utilizing these innovations can help meet the increasing demand for personalized nutrition solutions that enhance health and well-being.

3.4.6. Advanced genomics and proteomics

Leveraging genomics and proteomics to study LAB's metabolic pathways may optimize the production of specific peptides and bioactive compounds. These omics technologies offer insights into LAB's genetic and protein expression profiles, aiding in optimizing fermentation processes and developing products tailored to specific health outcomes.

Genomics reveals the genetic makeup of LAB, identifying genes responsible for bioactive compound production. For example, genomic analysis of *Lactococcus lactis* identified genes linked to lactic acid production, bacteriocin synthesis, and antimicrobial peptides that inhibit pathogens (Zhang et al., 2016). Similarly, genome-scale metabolic modeling combined with transcriptome profiling showed the importance of nitrogen sources in the fermentation processes of *Streptococcus thermophilus* (Rau et al., 2022). This genetic knowledge supports the selection or engineering of LAB strains to enhance specific metabolite production.

Proteomics complements genomics by revealing protein expression and post-translational modifications during fermentation. Proteomic analysis identifies enzymes involved in LAB's metabolic pathways, highlighting their activity under different conditions. For instance, studies have shown that enzymes crucial to lactic acid synthesis are upregulated during fermentation, guiding the optimization of pH and temperature to maximize bioactive compound yields (Zhang et al., 2016).

Optimization strategies include strain selection, adjusting fermentation conditions, and co-culture fermentation. Selecting LAB strains with desirable traits, such as high bacteriocin production, enhances fermentation efficiency, while genetic engineering methods like CRISPR/Cas allow for targeted strain improvements (Dong et al., 2022). Adjusting conditions like nitrogen source variations can boost LAB's proteolytic activity, increasing bioactive peptide release (Rau et al., 2022). Co-culturing LAB strains may enhance metabolic capabilities, leading to a broader range of bioactive compound production (Konstantinidis et al., 2021).

Due to high costs and complexity, integrating genomics and proteomics into routine fermentation remains challenging. Solutions include developing cost-effective sequencing technologies like next-generation sequencing (NGS), which provides comprehensive genomic data at reduced costs (Zhao et al., 2019). Streamlining data analysis with user-friendly bioinformatics tools can simplify omics data interpretation for researchers without computational expertise (Muynarsk et al., 2019). Collaborative research initiatives and training programs may promote the adoption of omics technologies, improving access within the food and beverage industry (Workie, 2020).

Genomics and proteomics offer a path for optimizing LAB fermentation processes to produce specific bioactive compounds. Addressing challenges related to cost and complexity may integrate these technologies into developing functional fermented foods tailored to individual health needs.

3.4.7. Regulatory and consumer acceptance

Developing novel fermented products in the expanding functional foods and nutraceuticals market faces regulatory challenges that can impede innovation and consumer acceptance. These difficulties stem from ensuring product safety, efficacy, and compliance with existing food regulations while meeting consumer demand for natural, health-promoting products.

The regulatory landscape for functional foods is complex and varies by region. Many countries lack a dedicated category for these products, complicating the approval process. In the United States, the FDA does not have a specific framework for functional foods, leading to approval delays of six to ten months (Martirosyan & Alvarado, 2023). This extended waiting period burdens manufacturers and hinders innovation. Unclear guidelines also leave producers uncertain about permissible safety and health claims (Martirosyan, Adany & Kanya, 2021). Novel fermented products must undergo rigorous testing to prove they pose no health risks, such as harmful microorganisms or metabolites (Francisco, 2024). This can further delay launches and increase costs, especially for smaller enterprises (Martirosyan, Adany & Kanya, 2021).

Consumer acceptance is another critical factor. As health consciousness rises, a growing demand for products is perceived as natural, safe, and beneficial. However, skepticism about new functional foods can slow acceptance. Consumers often trust established brands with proven safety records, making it challenging for new products to gain traction (Reyes-Díaz et al., 2018). Misinformation about food safety and health claims can dampen enthusiasm (Vinayamohan et al., 2023). Transparent communication about benefits and safety through educational campaigns can build consumer confidence (Pontieri et al., 2022).

Aligning scientific innovation with consumer demand is required. Consumer-centric product development ensures that new products meet preferences by conducting market research and incorporating feedback into formulations (Sari et al., 2019). Emphasizing natural ingredients and traditional fermentation methods while avoiding artificial additives can increase appeal and trust (Pontieri et al., 2022). Robust scientific evidence supporting health claims is vital; collaborating with research institutions to conduct clinical trials on bioactive compounds can validate claims and reassure consumers (Reyes-Díaz et al., 2018).

Regulatory advocacy is also a determinant. Engaging with regulatory bodies to advocate for more precise guidelines and faster approval processes can accelerate product innovation. Industry associations could allow a unified voice to be presented to address regulatory challenges (Martirosyan & Alvarado, 2023). Regulatory challenges and consumer acceptance present significant but manageable hurdles for introducing novel fermented products. By emphasizing transparency, utilizing natural ingredients, ensuring scientific validation, and engaging with regulatory authorities, the functional food industry can build consumer trust and successfully bring new products to the market.

3.4.8. Cross-disciplinary research

To address complex fermentation challenges in developing innovative food products, interdisciplinary collaboration among microbiologists, food scientists, nutritionists, and bioengineers is required. Such partnership requires strategic efforts, such as establishing common goals through workshops (Lorenzetti et al., 2022), using structured frameworks like a transdisciplinary approach (Felt et al., 2016), and promoting mutual learning through joint training sessions (LaPensee & Doshi, 2020).

Leveraging technology, such as project management software and data visualization tools, enhances communication (Pope et al., 2021), while institutional support through funding and resources facilitates collaboration (Mackey & McAllister, 2022).

Addressing barriers like disciplinary differences is also necessary for effective teamwork (Lanterman & Blithe, 2019). Fostering a culture of innovation through brainstorming sessions and design thinking workshops encourages creative solutions (LaPensee & Doshi, 2020). Applying these strategies can help develop functional foods that meet consumer health needs.

3.4.9. Utilization of cutting-edge technologies

Integrating artificial intelligence (AI) and machine learning (ML) into traditional fermentation systems enhances efficiency and predictability. This integration optimizes production processes and ensures cost-effectiveness for small-scale and industrial operations. AI and ML improve the predictive capabilities of fermentation systems by analyzing large datasets. For example, artificial neural networks (ANNs) effectively model and optimize production stages in bioethanol production, including pretreatment and fermentation (Owusu & Marfo, 2023). These technologies, leveraging historical data and real-time monitoring, predict optimal conditions, minimize waste, improve yield, and maintain product quality and market competitiveness (Gonzalez Viejo & Fuentes, 2020a, 2020b). AI also contributes to quality assessment and sensory analysis. Machine learning models combined with electronic noses can accurately assess beer quality and predict sensory traits based on chemical fingerprints, reducing costs associated with traditional quality control (Gonzalez Viejo & Fuentes, 2020a, 2020b).

Process automation further achieves cost-effectiveness. AI and ML facilitate automated control systems that adjust real-time parameters like temperature, pH, and nutrient levels, reducing labor costs and minimizing human error. Integrating Internet of Things (IoT) devices with AI enables continuous monitoring, making fermentation processes more responsive and efficient (Adeyeye & Akanbi, 2024). Ethical considerations must be addressed to ensure responsible AI and ML deployment in fermentation. Establishing frameworks for data privacy and algorithmic bias is crucial for transparency and accountability (Alibašić, 2023; Harishbhai Tilala et al., 2024), fostering stakeholder trust and broader acceptance of these technologies.

Integrating AI and ML into fermentation systems enhances production efficiency, automates workflows, and elevates quality, contributing to more sustainable and streamlined practices. To fully take advantage of these advancements, it is important to address the ethical implications involved.

3.4.10. Valorization of fermented by-products

Upcycling fermentation by-products into high-value products, such as dietary fibers and bioactive compounds, can improve sustainability in food production by reducing waste and contributing to the circular economy, which requires efficient and economically viable extraction and purification methods. Fermentation generates by-products like spent grains, fruit pomace, and residual biomass that can be upcycled. For example, BSG are rich in dietary fibers and proteins, making them suitable for producing functional food ingredients (Chin, Chai & Chen, 2022; Jackowski et al., 2020).

Solid-state fermentation of BSG can yield protein hydrolysates with enhanced antioxidant properties, adding market value (Chin, Chai & Chen, 2022). Similarly, berry pomace can extract bioactive compounds like flavonoids and dietary fibers to improve the nutritional value of baked goods (Rohm et al., 2015). Cocoa pulp fermentation by-products can be repurposed for novel beverages, adding value to the cocoa industry (Klis et al., 2023).

Table 4 Comparative overview of challenges and opportunities in wheat fermentation for antioxidant peptide production.

Main Topic	Key Aspects	Important Approaches
Optimization of Fermentation Processes	- Temperature and pH control - Starter culture selection - Sustainable practices	- Optimization to improve yield - Use of LAB and mixed cultures - Minimize carbon footprint using local sources and bioprocesses
Novel Substrates and By-products	- Use of cereal grains - Fermentation of camel milk - Food industry by-products	- Utilization of carbohydrate-rich materials - Fermentation of by-products like whey to reduce waste
Health-related Applications	- Bioactive peptides with anticancer, antioxidant, and antimicrobial properties - Clinical trials and bioavailability	- Development of efficient delivery systems - Importance of well-structured trials to validate benefits
Sustainability in Fermentation	- Use of renewable resources - Energy-efficient technologies - Integration into biorefineries	- Fermentation of biomass for nutraceuticals - Utilization of technologies like dark fermentation and condition optimization for efficiency
Personalized Nutrition	- Fermented foods tailored to individual health needs - Technologies for customization	- Use of specific probiotics for digestive health - Fermentation of products that improve metabolic health
Genomics and Proteomics	- Genetic analysis of LAB - Protein expression and activity during fermentation	- Application of genomic tools to optimize bioactive compound production - Strain selection and improvement
Regulatory and Consumer Acceptance	- Regulatory challenges - Consumer acceptance of functional foods	- Need for clear guidelines for production and labeling - Emphasis on natural ingredients to build trust
Advanced Technologies	- Integration of AI and ML - Process automation	- Use of predictive models to improve efficiency - Automation and continuous monitoring for optimization
Valorization of By-products	- Upcycling by-products into high-value products - Extraction and purification techniques	- Utilization of dietary fibers and bioactive compounds - Techniques like enzymatic hydrolysis and membrane separation to maximize value

Several strategies are essential to efficiently extracting and purifying bioactive compounds from fermentation by-products. Enzymatic hydrolysis, supercritical fluid extraction, and microwave-assisted extraction can increase yields while minimizing harmful solvents (Farooque et al., 2018). Advanced membrane separation technologies, like nanofiltration and ultrafiltration, allow for the selective removal of unwanted components, enhancing purification efficiency (Gonzales et al., 2022). Using cost-effective and biodegradable materials, such as natural adsorbents, further supports economic viability (Farooque et al., 2018). Integrated bioprocessing systems that combine fermentation, extraction, and purification steps can streamline operations and boost sustainability (Gugel et al., 2024).

Economic viability also depends on understanding market demands. With growing interest in functional foods and nutraceuticals, upcycled products present opportunities, especially for health-conscious consumers seeking natural, nutritious options. Communicating these products' sustainability and health benefits effectively can increase consumer acceptance, particularly as awareness of food waste issues rises (Nyhan et al., 2023).

Transforming fermentation by-products into high-value products such as dietary fibers and bioactive compounds could boost sustainability in food production. Using efficient extraction techniques, cutting-edge technologies, and an understanding of market trends, the food industry can convert waste into valuable assets, supporting the circular economy and aligning with consumer demands for natural, health-enhancing products.

Finally, **Table 4** comprehensively overviews the challenges and opportunities in wheat fermentation for antioxidant peptide production. It highlights critical aspects such as optimizing fermentation processes, utilizing novel substrates, addressing health-related applications, ensuring sustainability, and incorporating personalized nutrition.

The table also emphasizes the importance of genomics and proteomics, regulatory and consumer acceptance, advanced technologies, and by-product valorization. Addressing these challenges through targeted approaches, such as improving fermentation conditions, leveraging advanced technologies, and fostering regulatory clarity, presents opportunities for enhancing wheat-based fermented products' efficacy, sustainability, and consumer acceptance. These strategic efforts can lead to the successful integration of antioxidant peptides into functional food applications, meeting both industry standards and consumer health needs.

4. Concluding remarks and perspectives

The overall objective of this study was to perform a bibliometric analysis of LAB used in wheat fermentation to produce antioxidant peptides. It was found that there has been a growth in research on this topic from 2010 to 2023, with notable contributions from leading countries such as China and Italy. The bibliometric analysis revealed that the primary research themes included the optimization of fermentation processes, the characterization of bioactive peptides, and their potential health benefits. Solid-state fermentation was frequently investigated, highlighting its relevance in producing functional food ingredients. Furthermore, the data indicated a high level of international collaboration, which has been pivotal in advancing this field.

These findings concluded that research on lactic acid bacteria fermentation of wheat proteins is an expanding field with considerable potential for developing functional foods with health-promoting properties. However, challenges related to optimizing fermentation processes, sustainable practices, and regulatory acceptance remain.

In future research, further exploration of sustainable fermentation processes using novel substrates and the integration of advanced genomic tools for strain selection could be beneficial. Additionally, more studies focused on clinical validation of the health benefits of these bioactive peptides are necessary to support their use in nutraceutical and functional food products. Enhanced interdisciplinary collaboration is required to address the identified challenges and realize LAB's potential in food biotechnology.

Acknowledgments

The authors thank the Sistema Nacional de Investigadoras e Investigadores (SNII-SECIHTI), the Universidad Autónoma del Estado de Hidalgo (UAEH), and the Universidad Autónoma Metropolitana, Unidad Iztapalapa (UAM-I) for supporting this research. E.P.-E. thanks for the postdoctoral fellowship assigned to him.

Authors' Contributions

G.M.R.-S. and E.P.-E.: Conceptualization; J.G.P.-F. and Z.D.S.-M.: Data curation; E.C.-L. and A.A.-N.: Formal analysis; L.G.G.-O. and Z.D.S.-M.: Investigation; J.G.P.-F. and L.G.-C.: Methodology; J.G.P.-F.: Software; E.P.-E. and G.M.R.-S.: Supervision; L.G.G.-O. and A.A.-N.: Validation; E.P.-E. and E.C.-L.: Visualization; J.G.P.-F. and Z.D.S.-M.: Writing - original draft; E.P.-E. and L.G.-C.: Writing – review & editing. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Funding

No external funding was acquired for this project.

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