Food Science Today 4:1 (2025)
ISSN 2965-1190

REVIEW ARTICLE

FOOD SCIENCE TODAY

Application of bacteriocins in food preservation and safety: A bibliometric analysis approach

Aplicação de bacteriocinas na preservação e segurança de alimentos: uma abordagem de análise bibliométrica

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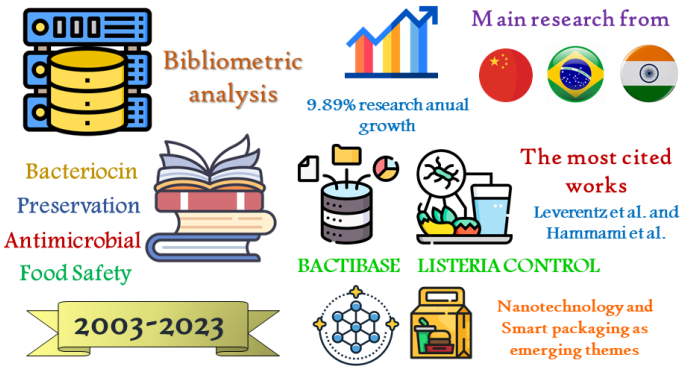
Abstract
The growing consumer demand for natural food preservatives has intensified research into bacteriocins, due to their potential to enhance food safety and preservation. This study aimed to conduct a bibliometric analysis of bacteriocin research from 2003 to 2023, focusing on their applications in food preservation to identify critical trends, challenges, and future directions. The analysis revealed a significant publication increase with an annual growth rate of 9.89% with countries like China, Brazil, and India as the leaders in contributions. Also, journals like “Food Control” and “Journal of Applied Microbiology” were major dissemination platforms. The research predominantly fell under Food Science Technology and Microbiology, with foundational studies by Leverentz et al. and Hammami et al. receiving high citations. Despite challenges such as pH sensitivity, thermal stability, and regulatory hurdles, advances in nanotechnology and collaborative global research are enhancing bacteriocin stability and efficacy. The study also identified emerging research themes, including integrating bacteriocins into antimicrobial packaging and their combination with other antimicrobial agents. The findings underscore the potential of bacteriocins as natural preservatives, driven by consumer demand for minimally processed foods and the need for sustainable food preservation strategies. In conclusion, while bacteriocins show promise, overcoming application and regulatory challenges is necessary for their broader integration into food safety strategies, aligning to promote sustainable and effective food preservation solutions.

Keywords: Antimicrobial peptides. Lactic acid bacteria. Bacteriocins. Food Safety. Bacteriocin stability. Foodborne pathogen control.

Resumo
A crescente demanda de consumidores por conservantes naturais de alimentos intensificou a pesquisa sobre bacteriocinas, devido ao seu potencial para melhorar a segurança e a preservação de alimentos. Este estudo teve como objetivo realizar uma análise bibliométrica da pesquisa sobre bacteriocinas de 2003 a 2023, com foco em suas aplicações na preservação de alimentos, para identificar tendências críticas, desafios e direções futuras. A análise revelou um aumento significativo nas publicações, com uma taxa de crescimento anual de 9.89%, com países como China, Brasil e Índia liderando as contribuições. Além disso, periódicos como "Food Control" e "Journal of Applied Microbiology" foram as principais plataformas de disseminação. A pesquisa se concentrou predominantemente em Ciência e Tecnologia de Alimentos, bem como Microbiologia, com estudos fundamentais de Leverentz et al. e Hammami et al. recebendo altas citações. Apesar de desafios como sensibilidade ao pH, estabilidade térmica e obstáculos regulatórios, os avanços em nanotecnologia e a pesquisa colaborativa global estão aprimorando a estabilidade e eficácia das bacteriocinas. O estudo também identificou temas emergentes de pesquisa, incluindo a integração de bacteriocinas em embalagens antimicrobianas e sua combinação com outros agentes antimicrobianos. Os resultados ressaltam o potencial das bacteriocinas como conservantes naturais, impulsionadas pela demanda do consumidor por alimentos minimamente processados e pela necessidade de estratégias sustentáveis de preservação de alimentos. Em conclusão, embora as bacteriocinas mostrem grande potencial, superar os desafios de aplicação e regulamentação é necessário para sua integração mais ampla em estratégias de segurança de alimentos, alinhando-se para promover soluções sustentáveis e eficazes de preservação de alimentos.

Palavras-chave: Peptídeos antimicrobianos. Bactérias ácido láticas. Bacteriocinas. Segurança de alimentos. Estabilidade de bacteriocina. Controle de patógenos transmitidos por alimentos.

Graphical Abstract



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

ROYALDATASET

1. Introduction

Bacteriocins, ribosomally synthesized antimicrobial peptides produced by various bacteria, mainly lactic acid bacteria (LAB), have garnered significant attention for their potential as natural preservatives in the food industry. These peptides exhibit a broad spectrum of antimicrobial activity, primarily targeting closely related bacterial species, including foodborne pathogens such as *Listeria monocytogenes*, *Bacillus cereus*, and *Staphylococcus aureus* (Anupama & Balasingh, 2018; da Costa et al., 2019; García-Curiel et al., 2021; Yu et al., 2023).

Bacteriocins are generally classified into three main classes based on their structure and mode of action, each offering unique advantages in food preservation. Class I bacteriocins, known as lantibiotics, are small peptides that undergo extensive post-translational modifications, incorporating unusual amino acids essential for their antimicrobial activity. Class II bacteriocins are small, heat-stable peptides that do not undergo such changes, making them highly valuable in food preservation due to their stability and effectiveness against closely related bacterial species. In contrast, Class III bacteriocins are larger, heat-labile proteins that lose their activity upon exposure to high temperatures but have a broader spectrum of activity, targeting a more comprehensive range of bacteria than the smaller peptides in Classes I and II (García-Curiel et al., 2021; García-Curiel, Rodríguez-Hernández, et al., 2024).

This classification highlights bacteriocins' diverse mechanisms and potential applications in enhancing food safety and prolonging shelf life through their natural antimicrobial properties. Bacteriocins' effectiveness is primarily due to their ability to form pores in bacterial membranes, interfere with cell wall synthesis, and disrupt essential cellular processes, giving the producing bacteria a competitive advantage in natural ecosystems (Mekala & Ansari, 2023; Onwuakor et al., 2014).

On the other hand, the growing consumer demand for minimally processed foods and natural preservatives has driven the application of bacteriocins in the food industry. Bacteriocins can significantly extend the shelf life of food products and reduce the risk of spoilage and pathogenic bacteria, making them a crucial tool in food safety (Wang et al., 2021; Yu et al., 2023). Various methods have been developed to apply bacteriocins in food preservation. These include directly adding purified bacteriocins, incorporating bacteriocin-producing LAB into food products, and using fermented ingredients that naturally contain bacteriocins (Garcha & Natt, 2012).

Nisin is one of the most studied bacteriocins. Due to its proven efficacy against various pathogens, it is widely used in dairy products and processed meats (Delesa, 2017). This versatility underscores the importance of bacteriocins in modern food preservation strategies, offering natural and effective alternatives to synthetic preservatives. In general, bacteriocins maintain advantages over other preservatives because they do not modify the sensorial characteristics at the concentration used and they can be combined with other natural preservatives (Daba et al., 2025; Efendi et al., 2024; Zaky & Mahmoud, 2019). Also, they have the benefit of being recognized as safe for human consumption, actually; however, more evidence in *in vivo* models is necessary to determine their influence in the gastrointestinal disorders (Benítez-Chao et al., 2021; Meade et al., 2020; Todorov et al., 2022).

Thus, integrating bacteriocins into food preservation aligns with the principles of hurdle technology, which combines multiple preservation methods to enhance food safety and quality. This approach improves the antimicrobial efficacy of bacteriocins and reduces reliance on synthetic preservatives, addressing consumer concerns regarding chemical additives (Sharma et al., 2020). Additionally, advancements in nanotechnology have improved the stability and delivery of bacteriocins, making their application more practical and effective in various food systems (Fahim et al., 2016; Shafique et al., 2022).

The food industry faces persistent challenges related to food spoilage and pathogen contamination, which can lead to significant economic losses and public health concerns. Microbial activity, including bacteria, molds, and yeasts, is the primary cause of food spoilage, while pathogens like *Escherichia coli*, *Salmonella*, and *Listeria monocytogenes* pose serious health risks, leading to widespread foodborne illnesses (Mokoena et al., 2021; Yu et al., 2023). Traditional preservation methods, such as refrigeration and chemical preservatives, are often insufficient to meet the growing demand for natural and minimally processed foods, prompting researchers and food manufacturers to explore alternative methods like bacteriocins (Abdulhussain Kareem & Razavi, 2020; Perez et al., 2014).

The research on bacteriocins has evolved significantly since their discovery, with early studies focusing on their characterization and antimicrobial properties. Over time, the focus has shifted to applied studies that explore their use in food preservation, including direct inoculation of bacteriocin-producing strains, the use of bacteriocin-containing fermentates, and the development of bacteriocin-infused packaging materials (Damania et al., 2016; Prudêncio et al., 2015). Nowadays, commercial bacteriocin such as Bactoferm™, Microgard™, and Nisaplin™ are used in diverse products from meat, fish, vegetables, and dairy industry, improving the shelf life of sausages, salami, ham, caviar, fresh-cut salads, fruit juices, yogurt, sour cream, buttermilk, dairy desserts, and different types of cheese like cottage, feta, mozzarella, white or fresh (da Costa et al., 2019; Delesa, 2017; Raj et al., 2022). Despite their promise, challenges such as pH sensitivity and narrow antimicrobial spectra remain, necessitating further research into novel bacteriocins and improved delivery systems (Shafique et al., 2022; Xin et al., 2020).

Bibliometric analysis is an essential method for evaluating the research landscape surrounding bacteriocins. It reveals publication trends, prominent research domains, and the progression of scientific discussions. Examining data from 2003 to 2023 allows researchers to pinpoint emerging trends and uncover gaps in literature, such as underexplored bacteriocin-producing strains or innovative applications in food safety (Abubakar et al., 2023). This systematic approach maps the current state of research and guides future investigations by highlighting areas that require further exploration.

In that context, this study aimed to conduct a bibliometric analysis to systematically evaluate the application of bacteriocins in food preservation and safety. To achieve this, primary research articles published between 2003 and 2023 were analyzed, excluding review articles and focusing on food conservation, shelf life, pathogen control, and antimicrobial effects. The analysis identified research trends, key contributions, and gaps in literature over the past two decades.

2. Methodology

The bibliometric analysis was conducted using the advanced search mode in Web of Science®, with a carefully crafted logical search string to capture relevant literature. The search string used was ‘TS = (((bacteriocin* AND "food*" AND ("application*" OR "conservation" OR "preservation" OR "shelf life" OR "stability")) AND ("pathogen" OR "spoilage" OR "antimicrobial" OR "food safety")) NOT (review OR overview OR "review article"

OR "literature review"))'. This logical expression was designed to identify studies focused on the application of bacteriocins in the food industry, particularly those related to food conservation, preservation, shelf life, and stability, while simultaneously addressing the role of bacteriocins in combating pathogens, spoilage, antimicrobial effects, and overall food safety.

Including “bacteriocin*” and “food*” was intended to narrow the search to articles discussing bacteriocins within a food context. The terms “application*”, “conservation”, “preservation”, “shelf life”, and “stability” were included to ensure the search captured a broad range of studies related to the practical use and impact of bacteriocins on food products. Additionally, the terms “pathogen”, “spoilage”, “antimicrobial”, and “food safety” were used to focus on research highlighting the efficacy of bacteriocins in protecting food from harmful microorganisms.

The NOT operator excluded reviews, overviews, and literature review articles, ensuring that only original research articles were included in the dataset. This approach was intended to gather primary research data that could be used for a more accurate and focused bibliometric analysis. The search was refined by excluding document types such as early access articles, publisher-invited reviews, book chapters, proceeding papers, retracted publications, and data papers.

Finally, the publication years were filtered to include articles from 2003 to 2023, providing a comprehensive view of the research trends over the past two decades. This methodology yielded a robust and relevant dataset for the subsequent bibliometric analysis (García-Curiel, Guadalupe Pérez Flores, et al., 2024; Pérez-Flores et al., 2024).

The search results were exported as a single BibTeX file (savedrecs.bib) to streamline the processing and analysis. This file contained essential information, including authors, titles, abstracts, keywords, affiliations, citations, and other relevant metadata. The bibliometric analysis was conducted on a PC running “elementary OS 7.1 Horus” (Linux 6.8.0-40-generic). For this analysis, R version 4.1.2 (2021-11-01) “Bird Hippie” was employed, utilizing the ‘bibliometrix’ package version 4.1.4 and its graphical interface, ‘biblioshiny’. The analysis used Rstudio® 2024.04.2+764 “Chocolate Cosmos” as the integrated development environment. The necessary libraries were loaded with the command library(bibliometrix), and the graphical interface was launched using ‘biblioshiny’.

3. Results and Discussion

3.1. Scientific production from 2003 to 2023 timespan

Table 1 provided a comprehensive overview of the data derived from the bibliometric analysis of bacteriocins in food preservation and safety, covering the period from 2003 to 2023. The dataset included 847 documents sourced from 251 different journals, books, and other outlets. The analysis revealed a notable annual growth rate of 9.89%, reflecting the increasing interest and expanding research activity in this area over the past two decades. The average age of the papers was 8.09 years, indicating that the field has been actively developed in recent years. The average number of citations per document was 25.24, suggesting that research on bacteriocins in food applications had a considerable scientific impact, with many studies being well-cited in the literature.

The contents of the documents were also analyzed, with “Keywords Plus” generating 1,723 terms and authors contributing 1,883 distinct keywords. These figures demonstrated the diverse range of topics and specific areas of interest explored within this field, highlighting the complexity and breadth of research on bacteriocins and their applications in food safety and preservation. Authorship analysis showed that 3,085 authors contributed to the 847 documents, with only eight being single-authored. This highlighted the highly collaborative nature of research in this domain. On average, each document involved 5.03 co-authors, emphasizing the collaborative efforts necessary to advance this field of study. Additionally, 27.74% of the papers resulted from international co-authorship, indicating significant global collaboration and the worldwide relevance of research on bacteriocins.

Table 1 Summary of bibliometric data on bacteriocin research in food preservation and safety on the 2003-2023 timespan

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2003-2023
Sources (Journals, Books, etc)	251
Documents	847
Annual Growth Rate %	9.89
Document Average Age	8.09
Average citations per doc	25.24
DOCUMENT CONTENTS	
Keywords Plus (ID)	1723
Author’s Keywords (DE)	1883
AUTHORS	
Authors	3085
Authors of single-authored docs	8
AUTHORS COLLABORATION	
Single-authored docs	9
Co-Authors per Doc	5.03
International co-authorships %	27.74
DOCUMENT TYPES	
Article	847

In terms of document types, all 847 documents were classified as articles. This focus on primary research underscored the ongoing nature of exploration and discovery in the field as researchers continued to produce new findings and contribute original knowledge to the body of literature on bacteriocins. The data in **Table 1** illustrates a robust and growing field of study characterized by significant international collaboration, diverse research topics, and a strong emphasis on original research. The substantial citation rates and the variety of keywords used further underscored the impact and importance of bacteriocin research in food preservation and safety.

Fig. 1 provides an overview of the scientific production of bacteriocins in food preservation and safety from 2003 to 2023, with Figure 1a specifically illustrating the annual publication trends during this period. The data revealed a steady increase in research activity and publications over the 20 years, reflecting the growing interest and expanding focus on bacteriocins in food safety and preservation. In the early years, the number of articles remained relatively modest, with 10 publications in 2003 and slight fluctuations in subsequent years, peaking at 26 articles in 2008.

However, a notable increase began in 2009, with 38 articles and consistent growth throughout the following decade. Particularly significant growth was observed from 2012 onward, where the number of publications consistently exceeded 40 articles per year, peaking at 81 in 2021 despite the COVID-19 pandemic. This surge in research output indicated a heightened focus on bacteriocins as natural preservatives in the food industry, likely driven by increasing consumer demand for natural and minimally processed foods. The slight decline observed in 2022, with 76 articles, and in 2023, with 66 articles, could suggest a plateau in publication rates or a potential shift in research focus. Nonetheless, the overall trend demonstrated a significant and sustained interest in applying bacteriocins for food preservation and safety, underscoring the importance of bacteriocins as a research topic with a clear trajectory of growing scientific inquiry aimed at exploring and optimizing their use in the food industry.

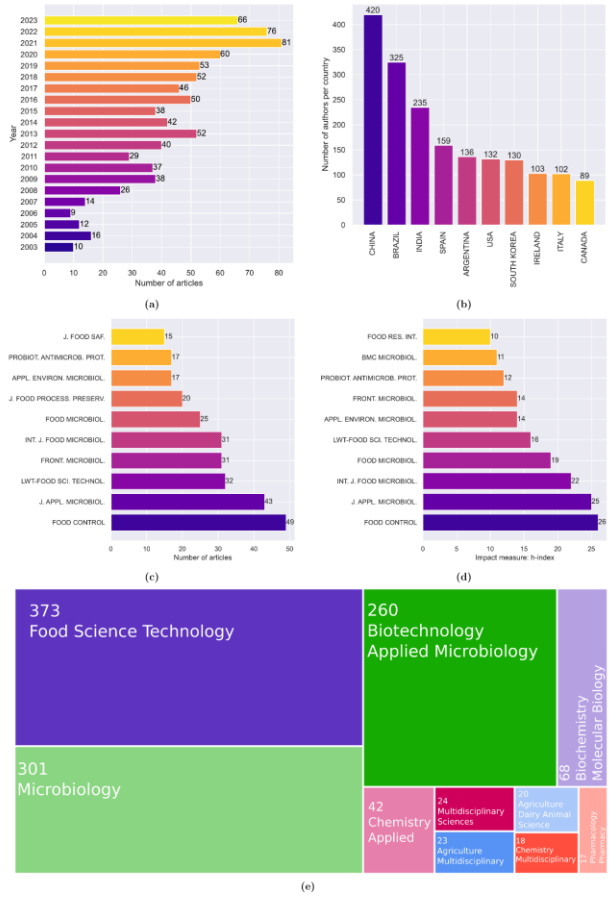

Fig. 1 Overview of scientific production in bacteriocin research, including annual publication trends from 2003 to 2023 (a), the number of authors per country (b), the most relevant sources (c), the h-index of the most pertinent journals (d), and the distribution of research across Web of Science® categories (e).

Fig. 1b illustrates the distribution of authors by country, revealing significant disparities in research contributions to bacteriocin studies across different regions. China led with 420 authors, followed by Brazil with 325 and India with 235, indicating these countries' vital research focus on this area. European countries such as Spain, with 159 authors, Italy, with 102, also made substantial contributions, while the USA and South Korea had 132 and 130 authors, respectively. Other countries like Ireland and Canada, with 103 and 89 authors, showed moderate participation in the research. This distribution highlighted the global interest in bacteriocin research, with a notable activity concentration in specific regions, particularly in Asia and South America. The data suggested a significant engagement in bacteriocin research across these countries, reflecting their commitment to advancing food preservation and safety knowledge.

Fig. 1c depicts the distribution of articles across the most relevant journals in bacteriocins in food preservation and safety. Food Control was the leading journal, with 49 articles indicating its significant role in publishing research on this topic. Journal of Applied Microbiology followed closely with 43 articles, reflecting its importance in disseminating applied microbiological studies related to food safety. LWT - Food Science and Technology and Frontiers in Microbiology published 32 and 31 articles demonstrating their relevance in food technology and microbiology research. Similarly, the International Journal of Food Microbiology also contributed 31 articles, underscoring its focus on microbial aspects of food safety. Other notable journals included Food Microbiology, with 25 articles; Journal of Food Processing and Preservation, with 20 articles; Applied and Environmental Microbiology and Probiotics and Antimicrobial Proteins, with 17 articles; the Journal of Food Safety, with 15 articles. This distribution highlighted the key platforms where research on bacteriocins was most frequently published, indicating the journals that have been pivotal in advancing the field.

Fig. 1d illustrates the h-index values of the most relevant journals in bacteriocins in food preservation and safety. Food Control had the highest h-index of 26, indicating its strong influence and the high impact of its published articles. Journal of Applied Microbiology followed closely with an h-index of 25, reflecting its significant role in the field. International Journal of Food Microbiology had an h-index of 22, showing its substantial contribution to research on food microbiology. Food Microbiology and LWT - Food Science and Technology had h-index values of 19 and 16, respectively, indicating their relevance but slightly lower impact than the top journals. Other journals, such as Applied and Environmental Microbiology and Frontiers in Microbiology, had an h-index of 14, highlighting their importance in microbiological research, though with varying focuses and periods. The remaining journals, including Probiotics and Antimicrobial Proteins, BMC Microbiology, and Food Research International, had h-index values ranging from 10 to 12, suggesting a more specialized but impactful role in disseminating bacteriocin research. Overall, the h-index values underscored the critical journals that have driven the research and development in bacteriocins.

Fig. 1e illustrates the distribution of research articles on bacteriocins across various Web of Science® categories, highlighting the interdisciplinary nature of this field. Most publications, 43.575%, were categorized under Food Science Technology, indicating a primary focus on food preservation and safety. Microbiology accounted for 35.164% of the records, emphasizing the significant role of microbial studies. Biotechnology Applied Microbiology contributed 30.374%, underscoring the importance of biotechnological approaches. Smaller contributions in categories like Biochemistry Molecular Biology (7.944%), Chemistry Applied (4.907%), and Multidisciplinary Sciences (2.804%) demonstrated a broad scientific interest in bacteriocins beyond food technology. Other fields, such as Agriculture, Pharmacology, and Veterinary Sciences, each contributed between 1.5% and 2.7%, reflecting the diverse applications of bacteriocins in various scientific domains. The distribution revealed that while food science and microbiology were the primary research focuses, bacteriocin research also intersected with multiple disciplines, showcasing its wide-ranging impact and potential applications.

This section combines bibliometric analysis with an in-depth review of critical publications and research trends. While initial figures illustrate the overall growth and distribution in bacteriocin research, analyzing the most cited documents delves into the pivotal studies that have shaped the field, offering a comprehensive view of its evolution over the past two decades. **Table 2** summarizes the most globally cited documents related to bacteriocin research, highlighting the significant impact of these studies within the scientific community.

The paper by Leverentz et al. (2003) in Applied and Environmental Microbiology received the highest total citations, with 311 citations, averaging 14.14 per year and a normalized citation count of 4.45, reflecting its long-standing influence in the field. This research focused on controlling *Listeria monocytogenes* in fresh-cut produce. It evaluated a *Listeria*-specific lytic phage cocktail with the bacteriocin nisin on honeydew melons and Red Delicious apples stored at 10°C for 7 days. Nisin and phage cocktail reduced bacterial populations, especially on melons with higher pH. Phage sprays were more effective and enhanced with magnesium, while nisin worked better at lower pH. The

combination achieved up to 5.7 log reductions on melons and 2.3 on apples, suggesting it is an eco-friendly alternative to chemical sanitizers for pathogen control in fresh produce(Leverentz et al., 2003).

Table 2 Top 10 most cited articles in bacteriocin research with citation metrics.

Article	Journal	Total Citations (TC)	TC per Year	Normalized TC	Reference
Biocontrol of *Listeria monocytogenes* on fresh-cut produce by treatment with lytic bacteriophages and a bacteriocin	Applied and Environmental Microbiology	311	14.14	4.45	Leverentz et al. (2003)
BACTIBASE second release: a database and tool platform for bacteriocin characterization	BMC Microbiology	264	17.6	7.18	Hammami et al. (2010)
Monitoring of microbial metabolites and bacterial diversity in beef stored under different packaging conditions	Applied and Environmental Microbiology	207	14.79	5.64	Ercolini et al. (2011)
Biodegradable polylactic acid polymer with nisin for use in antimicrobial food packaging	Journal of Food Science	206	12.12	4.84	Jin and Zhang (2008)
Isolation and identification of a *Paenibacillus polymyxa* strain that coproduces a novel lantibiotic and polymyxin	Applied and Environmental Microbiology	169	9.39	3.64	He et al. (2007)
Antimicrobial activity of lactic acid bacteria isolated from Tenerife cheese: initial characterization of plantaricin TF711, a bacteriocin-like substance produced by *Lactobacillus plantarum* TF711	Journal of Applied Microbiology	152	7.6	2.71	Hernández et al. (2005)
Antimicrobial activity of a nisin-activated plastic film for food packaging	Letters in Applied Microbiology	143	7.15	2.55	Mauriello et al. (2005)
Combined antimicrobial effect of essential oils and bacteriocins against foodborne pathogens and food spoilage bacteria	Food Research International	137	10.54	4.13	Turgis et al. (2012)
Physical–mechanical and antimicrobial properties of nanocomposite films with pediocin and ZnO nanoparticles	Carbohydrate Polymers	136	11.33	4.48	Espitia et al. (2013)
Prevalence and characterization of *Enterococcus* spp. isolated from Brazilian foods	Food Microbiology	130	7.65	3.06	Gomes et al. (2008)

The study from Hammami et al. (2010) in BMC Microbiology followed closely with 264 total citations, the highest annual citation rate of 17.60, and the highest normalized citation count of 7.18, underscoring its strong relevance and consistent impact since publication. This research aimed to develop BACTIBASE, an open-access database offering detailed information on bacteriocins, including their distribution, net charge, and amino acid content across various organisms. The database expanded by 44%, adding 177 new bacteriocin sequences and introducing features like homology searches, multiple sequence alignments, molecular modeling, and a taxonomy browser. These enhancements were designed to support research in food preservation, safety applications, and drug development. BACTIBASE was ultimately launched online to advance the understanding and application of bacteriocins in microbiology.

Ercolini et al. (2011) also published in Applied and Environmental Microbiology, garnered 207 citations, with an annual rate of 14.79 and a normalized count of 5.64, showcasing its importance in microbiological applications of bacteriocins. Jin & Zhang (2008) in the Journal of Food Science and He et al. (2007) in Applied and Environmental Microbiology were also highly cited, with 206 and 169 total citations, respectively, maintaining strong annual citation rates and notable normalized citation counts, indicating their significant contributions to food science and microbiology. Ercolini et al. (2011) focused on using high-throughput sequencing to analyze the bacterial diversity in beef chops and monitoring their changes when bacteriocin-activated antimicrobial packaging was used, highlighting its potential for improving food safety and quality control. Jin & Zhang (2008) examined the antimicrobial properties of bacteriocins, particularly their role in inhibiting foodborne pathogens, emphasizing their potential for use in food preservation strategies. Both studies contributed to advancing bacteriocin research, offering practical insights into their application for enhancing food safety.

The remaining papers, such as those by Hernández et al. (2005) in the Journal of Applied Microbiology and Mauriello et al. (2005) in Letters in Applied Microbiology, while receiving fewer total citations, still demonstrated substantial influence with consistent citation rates over the years. Notably, Turgis et al. (2012) in Food Research International and Espitia et al. (2013) in Carbohydrate Polymers showed strong citation performance, reflecting their relevance in food preservation research. Gomes et al. (2008) in Food Microbiology rounded out the list with 130 citations, highlighting its ongoing contribution to the field.

The documents listed in **Table 2** were recognized as foundational works in bacteriocin research. Their citation metrics underscore their lasting impact and importance across various subfields, including microbiology, food science, and applied biotechnology.

3.2. Authors' keywords analysis

Fig. 2 presents the authors' keyword analysis results. **Fig. 2a** displays a word cloud representing the 50 most frequent terms used in the authors' keywords, providing insight into the primary themes and focus areas within bacteriocin research.

The term "lactic-acid bacteria" appeared with the highest frequency, occurring 251 times, underscoring the central role of these microorganisms in the study of bacteriocins. Other prominent terms included "purification" (193 occurrences) and "listeria-monocytogenes" (163 occurrences), reflecting significant research interest in the methods for isolating bacteriocins and their effectiveness against specific pathogens. "Food" (129 occurrences) and "preservation" (71 occurrences) were also frequently mentioned, indicating a strong emphasis on the application of bacteriocins in food safety and shelf-life extension.

Specific bacteriocins such as "nisin" (163 occurrences) and related activities like "antimicrobial activity" (85 occurrences) were commonly referenced, highlighting their importance in this field. The appearance of terms like "identification" (132 occurrences) and "growth" (100 occurrences) suggested ongoing efforts in characterizing and understanding bacteriocins' biological functions. Additionally, terms such as "strain", "inhibition", "resistance", and "biosynthesis" further emphasized the diverse research interests, from exploring the genetic basis and production of bacteriocins to their practical applications in combating microbial resistance and spoilage. The presence of "milk", "meat", and "cheese" indicated the relevance of bacteriocins in various food matrices.

Fig. 2b is a thematic map that categorizes the most significant research themes in bacteriocin studies into four quadrants based on their development degree (density) and

relevance (centrality). The quadrants represent different themes: Motor Themes, Basic Themes, Niche Themes, and Emerging or Declining Themes. In the Motor Themes quadrant, which represents well-developed and essential topics, "listeria-monocytogenes", "nisin", and "growth" are prominent. These terms are critical in bacteriocin research, indicating that studies focusing on these areas are central and mature, driving the field forward.

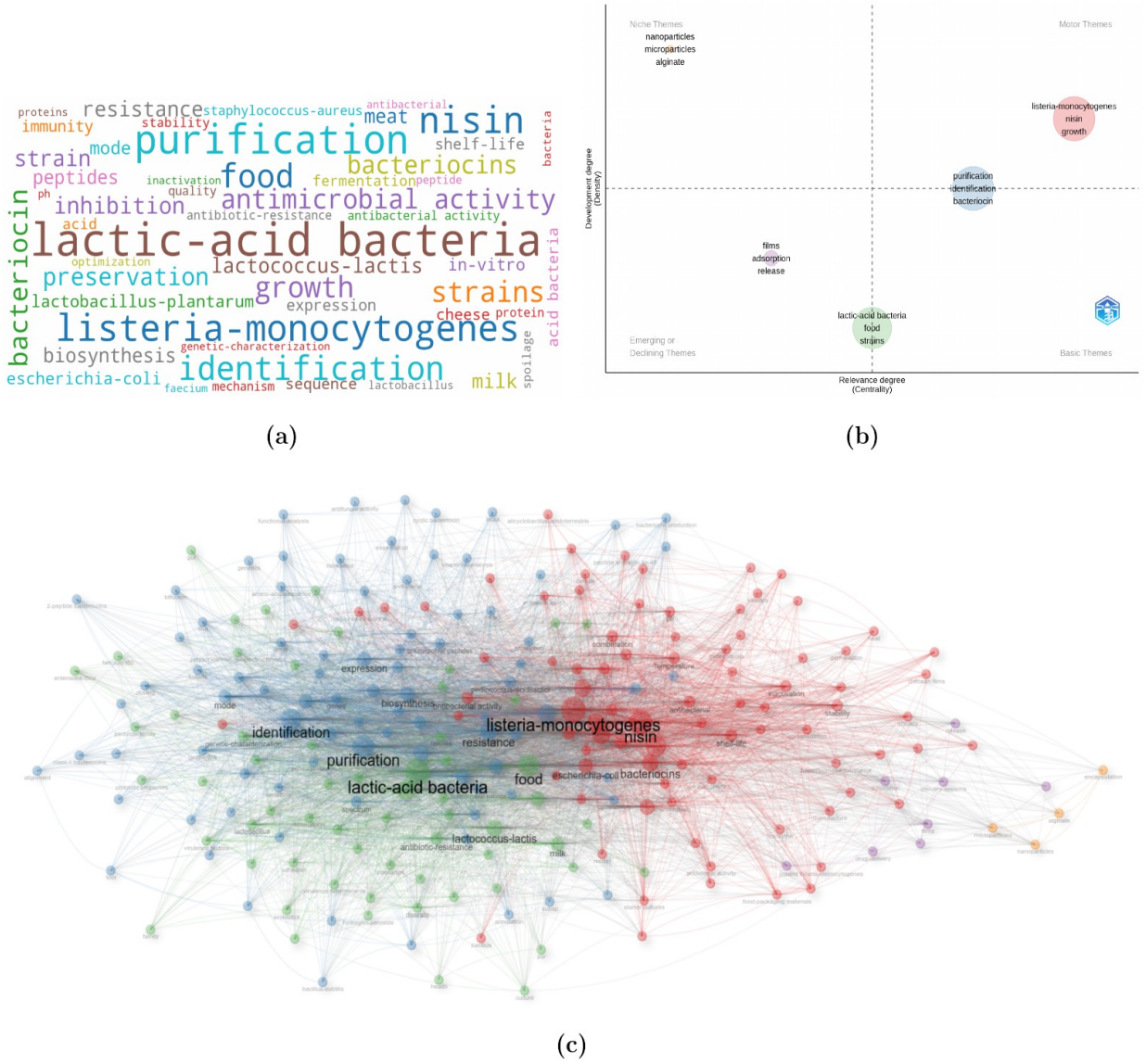

Fig. 2 Overview of authors' keyword analysis in bacteriocin research. (a) Word cloud showing the 50 most frequent terms used in the field. (b) Thematic map categorizes research themes into quadrants based on development and relevance. (c) Network visualization of frequent terms, organized into clusters representing central themes and their interconnections.

The Basic Themes quadrant includes fundamental and relevant topics with lower density and features terms like "purification", "identification", and "bacteriocin". These themes are essential to the field, forming the foundational knowledge that underpins more specific or advanced studies. In the Niche Themes quadrant, which includes highly specialized but less central topics, terms such as "nanoparticles", "microparticles", and "alginate" are found. These represent advanced, possibly cutting-edge areas that, while not yet central to the field, offer potential for future growth and development.

Finally, the Emerging or Declining Themes quadrant, which includes themes that are either emerging or losing relevance, contains terms like "films", "adsorption", and "release". These may represent new areas of interest that are not yet fully developed or are losing prominence in the field.

Interestingly, terms such as "lactic-acid bacteria", "food", and "strains" are positioned near the boundary of the Basic Themes and Emerging or Declining Themes quadrants, suggesting that while they are fundamental, their role might be evolving or becoming less central as the field progresses.

Fig. 2c presents a network visualization of the most frequent terms in bacteriocin research, organized into distinct clusters that reveal the central themes and their interconnections within the field. The analysis identified five major clusters, each representing a unique focus area within the broader domain of bacteriocins. The largest and most central cluster, labeled "listeria-monocytogenes", dominated the network with a high Callon Centrality score of 6.29 and the highest frequency of occurrences (1,638). This cluster includes terms like "listeria-monocytogenes", "nisin", and "growth", which are critical in the study of bacteriocins, particularly in the context of food safety and preservation. The high centrality of this cluster indicates its pivotal role in driving research and its strong connections to other themes, reflecting its

importance in understanding the antimicrobial effectiveness of bacteriocins against significant foodborne pathogens.

The "purification" cluster is the second most prominent, with a Callon Centrality of 5.42 and 1,595 occurrences. This cluster encompasses terms related to the biochemical and microbiological processes involved in isolating and characterizing bacteriocins, such as "purification", "identification", and "bacteriocin". The high density of this cluster suggests that it is a well-developed area of research, with significant contributions to the foundational knowledge required for advancing bacteriocin applications.

Another key area is the "lactic-acid bacteria" cluster, with a Callon Centrality of 4.78 and 1,177 occurrences. This cluster includes terms such as "lactic-acid bacteria", "food", and "strains", indicating a focus on the microbial sources of bacteriocins and their application in various food products. The centrality and frequency of this cluster highlight the importance of lactic acid bacteria as both producers of bacteriocins and as a subject of study in food microbiology.

Smaller clusters, such as "films" and "nanoparticles", represent more specialized research areas. The "films" cluster, with a Callon Density of 21.70, includes terms like "films", "adsorption", and "release", pointing to studies focused on the use of bacteriocins in food packaging and preservation systems. Though less central, the "nanoparticles" cluster shows a high Callon Density of 26.94, indicating a niche but rapidly developing research area where bacteriocins are integrated with nanotechnology for enhanced delivery and stability.

The combined analysis of the word cloud, thematic map, and network visualization was used to underscore a comprehensive and interconnected research landscape in bacteriocin studies. These visualizations highlighted the intense focus on practical applications, particularly in food safety, alongside the biological mechanisms and purification processes central to bacteriocin efficacy. The thematic map and network analysis revealed the balance between well-established areas of study and emerging topics, indicating the depth and evolving nature of bacteriocin research, with implications expected to continue shaping the field's future directions.

3.3. Factorial analysis

Fig. 3 presents a conceptual structure map generated using Multiple Correspondence Analysis (MCA). It visually represents the relationships between key terms in bacteriocin research. The map is divided into dimensions that capture the variance in the dataset, with terms grouped based on their association and centrality within the field.

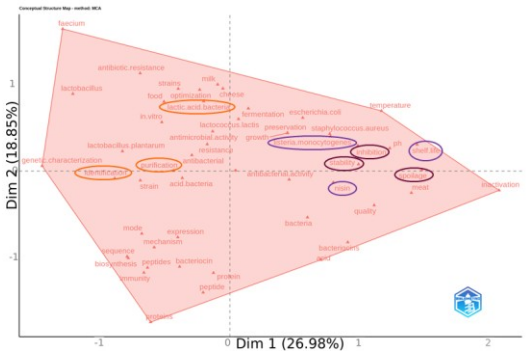

Fig. 3 Conceptual structure map of bacteriocin research using Multiple Correspondence Analysis (MCA).

The dataset reveals that terms like "listeria-monocytogenes", "nisin", and "shelf-life" are positioned towards the positive end of Dimension 1, indicating their strong relevance in studies focused on food preservation and safety, particularly in understanding the role of bacteriocins against pathogens. The proximity of terms such as "stability", "inhibition", and "spoilage" to these keywords further underscores their interconnectedness in the context of extending food shelf life and ensuring safety.

On the opposing end of Dimension 1, terms like "lactic-acid bacteria", "identification", and "purification" are grouped, reflecting their association with the microbial and biochemical characterization of bacteriocins. This suggests that research in this area is heavily focused on understanding the fundamental properties of bacteriocins, including their microbial origins and purification processes.

Dimension 2, which explains additional variance in the data, places terms such as "faecium", "antibiotic resistance", and "milk" towards the positive axis, highlighting their importance in studies related to bacterial resistance and dairy applications. Conversely, terms like "proteins", "peptide", and "bacteriocin" are positioned negatively on Dimension 2, which may indicate a focus on the molecular and genetic aspects of bacteriocin research, including their biosynthesis and functional mechanisms.

The map's layout, particularly the clustering of terms, complements the findings from **Fig. 2a** and **Fig. 2b**. It reinforces the centrality of food safety and pathogen control in bacteriocin research while highlighting the significance of molecular and microbial studies in advancing the field. The close relationship between these clusters illustrates the multidimensional nature of bacteriocin research, where applications in food preservation are deeply intertwined with fundamental scientific investigations into bacteriocin properties and mechanisms.

3.4. Future perspectives and challenges in bacteriocin application

Bacteriocins have emerged as promising natural preservatives, particularly in comparison to synthetic and other natural preservatives. Their safety profile is an advantage, as they are generally recognized as safe (GRAS) by regulatory agencies such as the FDA, given their proteinaceous nature and digestibility, which reduces health risks associated with synthetic preservatives (O'Connor et al., 2015; Thapar & Kumar Salooja, 2023). Furthermore, bacteriocins do not affect the sensory qualities of food, contributing to higher consumer acceptance, particularly in the context of increasing demand for natural, minimally processed products (Lahiri et al., 2022; O'Connor et al., 2015). This consumer preference is driven by a desire for clean labels and transparency in food production (Silva et al., 2018; Wang et al., 2021).

The large-scale application of bacteriocins in the food industry faces several challenges, primarily related to their pH sensitivity, thermal stability, and narrow spectrum of action, significantly impacting their effectiveness as natural preservatives. Bacteriocins exhibit varying degrees of stability across different pH levels, typically showing optimal activity within a neutral pH range, but their effectiveness diminishes in more acidic or alkaline conditions, limiting their use in acidic foods like pickles or fermented products (Chen, 2019; Md Sidek et al., 2018).

Thermal stability is another critical factor, as some bacteriocins, such as nisin, can withstand heat, while others lose their antimicrobial properties after exposure to high temperatures, complicating their use in processes like pasteurization (Kumar et al., 2012; Perez et al., 2021). Additionally, the narrow spectrum of

action, often limited to specific bacterial strains, necessitates the development of bacteriocins with broader inhibitory spectra to target diverse foodborne pathogens and spoilage organisms effectively (Koniuchovaitė et al., 2023; Soenarno et al., 2022).

These limitations and potential resistance among target pathogens pose significant barriers to implementing bacteriocins in the food industry. Despite being non-toxic, these challenges must be addressed through innovative approaches such as engineering chimeric bacteriocins or using nanotechnology for encapsulation to enhance their stability and efficacy in various food applications (Mills et al., 2017; Paškevičius et al., 2022; Zorič Peternel et al., 2010).

The concept of immune mimicry in the context of bacteriocins raises significant concerns regarding their safety, especially when these antimicrobial peptides are incorporated into food products. Since bacteriocins may elicit immune responses similar to those triggered by bacterial toxins, it is crucial to thoroughly investigate their immunogenicity to avoid potential adverse effects in consumers (Soltani et al., 2021; Thapar & Kumar Salooja, 2023). Some bacteriocins have been shown to possess properties that could potentially trigger immune pathways similar to those activated by pathogenic bacteria (Heinzinger et al., 2023). This phenomenon raises questions about whether regularly consuming foods containing bacteriocins could lead to sensitization or other immune-related issues in susceptible populations (Chen et al., 2020).

The safety of bacteriocins is further complicated by their potential interactions with other food components and preservatives. For example, combining bacteriocins with chemical preservatives or other antimicrobial agents can enhance their effectiveness and modify their immunogenic properties (Yu et al., 2023). Moreover, combining bacteriocins with other antimicrobial agents has produced synergistic effects that improve food safety and shelf life. This is particularly relevant in meat and dairy products, where bacteriocins and chemical preservatives have been found to inhibit spoilage and pathogenic bacteria effectively (Da Costa et al., 2019).

The regulatory landscape for bacteriocins, particularly in the context of obtaining FDA approval, presents significant challenges for newer candidates despite their promising antimicrobial properties. Newer bacteriocins must undergo rigorous evaluation, often necessitating extensive research to demonstrate their long-term safety, potential allergenicity, and effectiveness across different food matrices (Soltani et al., 2022).

Bacteriocin production can be labor-intensive and costly compared to nisin, which has established efficient and scalable production methods. The extraction and purification processes can be more complex for many bacteriocins, requiring advanced techniques that increase production costs and time (Twomey et al., 2021). This complexity affects the economic feasibility of bringing these bacteriocins to market and raises concerns about their consistency and quality, which are critical factors for regulatory approval (Soltani et al., 2021).

Recent innovations in bacteriocin delivery technology, particularly nanoencapsulation and integrating bacteriocins into novel packaging materials, have significantly advanced their potential for practical use in food preservation. Nanoencapsulation, which involves enclosing bacteriocins within nanostructured materials, has been shown to protect these antimicrobial peptides from environmental factors like heat, light, and pH changes, thereby enhancing their stability and prolonging their activity in food products (Mapelli et al., 2019). Using nanocarriers, such as nanoparticles or nanofibers, not only improves antimicrobial properties but also allows for controlled release, ensuring sustained activity over extended periods (Sidhu & Nehra, 2020; Sulthana & Archer, 2021).

Concurrently, the development of active packaging materials, including cellulose nanofibers combined with bacteriocins, has demonstrated effective antimicrobial action against foodborne pathogens such as *Listeria monocytogenes*, significantly enhancing food safety and shelf life (Becerril et al., 2020; Contessa et al., 2021; Mapelli et al., 2019). Additionally, the use of bacteriocin-capped silver nanoparticles has emerged as a promising approach to amplify antimicrobial efficacy by leveraging the synergistic effects of bacteriocins and silver nanoparticles, addressing some limitations like narrow spectrum activity and sensitivity to proteolytic enzymes (Sidhu & Nehra, 2020; Sulthana & Archer, 2021). However, challenges remain, particularly regarding the regulatory approval of new packaging materials and potential nanoparticle toxicity. This necessitates further research to optimize formulations and ensure long-term effectiveness while exploring eco-friendly and biodegradable packaging solutions to meet consumer demand for sustainable food packaging (Porta et al., 2022; Soltani et al., 2021).

Global collaboration has significantly advanced bacteriocin research, driving practical applications in food preservation. Bacteriocins, antimicrobial peptides produced by various bacterial strains, mainly LAB, have gained attention for their potential as natural preservatives. Collaborative efforts among researchers worldwide have facilitated the discovery of novel bacteriocins and improved methods for their production and application in food systems, with genome mining and mass spectrometry playing critical roles in identifying new bacteriocins and enhancing the efficacy of existing ones (O'Connor et al., 2015, 2020).

Innovations in encapsulation techniques, spurred by this global research environment, have further improved bacteriocin stability and activity during food processing (O'Connor et al., 2015; Shafique et al., 2022). However, despite identifying numerous bacteriocins, nisin remains the only one widely recognized and utilized in the food industry (Perez et al., 2014; Soltani et al., 2021). This limited utilization is partly due to a lack of awareness of bacteriocins' capabilities and reliance on traditional preservation methods (Chikindas et al., 2018; Perez et al., 2014). Nonetheless, global collaboration has fostered a greater understanding of bacteriocins' potential, gradually shifting toward their incorporation as preservatives in food products (Mekala & Ansari, 2023; Zhang et al., 2022).

Regulatory challenges remain, as the stringent approval processes by agencies like the FDA, which have only approved nisin, underscore the cautious approach towards bacteriocins due to concerns about safety and toxicity (Elalem, 2021; Soltani et al., 2021). While essential for consumer safety, this regulatory scrutiny also poses a barrier to broader adoption in the food industry (Md Sidek et al., 2018; Soltani et al., 2021). Risk assessments must consider bacteriocin production methods, potential interactions with food components, and specific microbial contexts, as the complexity of food matrices can influence their effectiveness (Md Sidek et al., 2018; Shafique et al., 2022). As research continues to clarify bacteriocins' mechanisms of action and safety profiles, regulatory frameworks are likely to evolve, potentially creating a more favorable environment for their use in food preservation (Soltani et al., 2021; Thapar & Kumar Salooja, 2023).

Another concern for worldwide regulatory agencies has been determining the bacteriocins added to commercialized products in recent years. In this context, nisin and natamycin from trademarks have been analyzed in some products from local

markets. Wee et al. (2024) determined nisin and its metabolites in flavored yogurts sold in Singapore because there is evidence of oxidation of the preservative in these products. In the same way, Şanlı et al. (2022) analyzed the Turkish dairy products sold in that country, found the presence of this bacteriocin in ayran, yogurt, and Kashar cheese. On the other hand, products with added strains capable of producing bacteriocin are equally important, although they have not been evaluated. An actual example is the development of Labhne with *Lactiplantibacillus plantarum* addition (Daba et al., 2025), a strain that produces a bacteriocin, improving the product's shelf-life. The study assesses physical-chemical and sensorial analyses; however, a safety test must be performed for commercialization.

Emerging research areas in bacteriocin applications increasingly focus on integrating with other preservation technologies to enhance food safety and extend shelf life. One promising direction is the combination of bacteriocins with natural preservatives or other antimicrobial agents. Studies have shown that combining bacteriocins with chemical substances can effectively control foodborne pathogens, reduce drug resistance, and broaden the antibacterial spectrum of these peptides (Yu et al., 2023). This synergistic approach enhances bacteriocins' efficacy while addressing limitations like their narrow antimicrobial spectrum and sensitivity to proteolytic enzymes (Sulthana & Archer, 2021).

Developing bacteriocin nanoconjugates, where bacteriocins are encapsulated in nanoparticles, further improves their stability and delivery, enhancing antimicrobial properties against food spoilage microorganisms (Sulthana & Archer, 2021). Additionally, exploring novel bacteriocins from diverse sources, such as marine environments and fermented products, is gaining traction. For example, new bacteriocins from the gut microbiome of marine fish present opportunities for discovering peptides with unique properties for food preservation (Sarika et al., 2018; Song et al., 2022). Characterizing bacteriocins derived from LAB has shown promise in inhibiting biofilm formation by foodborne pathogens, a significant challenge in food safety (Pang et al., 2022).

Thus, while bacteriocins hold significant promise as natural preservatives, their widespread application in the food industry is contingent upon overcoming several vital challenges. Integrating bacteriocins with other preservation technologies, such as nanotechnology and synergistic antimicrobial agents, is necessary for enhancing their efficacy and addressing pH sensitivity, thermal stability, and a narrow spectrum of action limitations. Furthermore, ongoing international collaboration in bacteriocin research and advancements in regulatory frameworks will be critical for promoting the widespread use of these natural antimicrobials. As research expands into novel bacteriocin sources, such as marine environments and LAB, and further innovations in encapsulation and delivery methods are developed, the potential for bacteriocins to become a cornerstone of food safety and preservation strategies is increasingly within reach.

4. Concluding remarks and perspectives

The bibliometric analysis of bacteriocin research from 2003 to 2023 was conducted to assess the growth and impact of this field, particularly in the context of food preservation. It was found that there was a significant annual growth rate of 9.89% in publications, with a total of 847 documents published across 251 sources. The research was collaborative, with an average of 5.03 co-authors per document and 27.74% of papers resulting from international collaborations. Key contributions were made by journals such as Food Control, which led in both the number of publications and impact.

The research primarily focused on the role of lactic acid bacteria, purification methods, and the effectiveness of bacteriocins against pathogens like *Listeria monocytogenes*. Notable studies by Leverentz et al. and Hammami et al. were frequently cited for their practical applications in food safety and preservation. Despite challenges related to pH sensitivity, thermal stability, and narrow antimicrobial spectra, innovations such as nanoencapsulation and active packaging were explored to enhance the strength and efficacy of bacteriocins.

Looking ahead, research perspectives in the field of bacteriocins involve addressing regulatory challenges and further fostering global collaboration to integrate bacteriocins into food preservation strategies. Future directions include combining bacteriocins with other preservation technologies and exploring novel sources to maximize their potential in food safety. Continued interdisciplinary research and international partnerships are necessary in advancing the application of bacteriocins as natural preservatives, ultimately contributing to safer and more sustainable food systems.

Acknowledgments

The authors thank the Sistema Nacional de Investigadoras e Investigadores (SNII-SECIHTI) and the Universidad Autónoma del Estado de Hidalgo (UAEH) for supporting this research. They dedicate this research to the memory of Dr. Santiago Ricardo Tomás Filardo Kerstupp (1945-2021).

Authors' Contributions

L.G.-C. and E.P.-E.: Conceptualization; J.G.P.-F. and G.H.-L.: Data curation; E.C.-L. and G.H.-L.: Formal analysis; L.G.G.-O. and G.H.-L.: Investigation; J.G.P.-F. and L.G.-C.: Methodology; J.G.P.-F.: Software; E.P.-E. and M.C.E.-R.: Supervision; L.G.G.-O. and M.C.E.-R: Validation; E.P.-E. and E.C.-L.: Visualization; J.G.P.-F. and G.H.-L.: Writing - original draft; E.P.-E.: 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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