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Whey as a functional ingredient in the food industry: a bibliometric study on its potential and innovation

Soro de leite como ingrediente funcional na indústria alimentícia: um estudo bibliométrico sobre seu potencial e inovação

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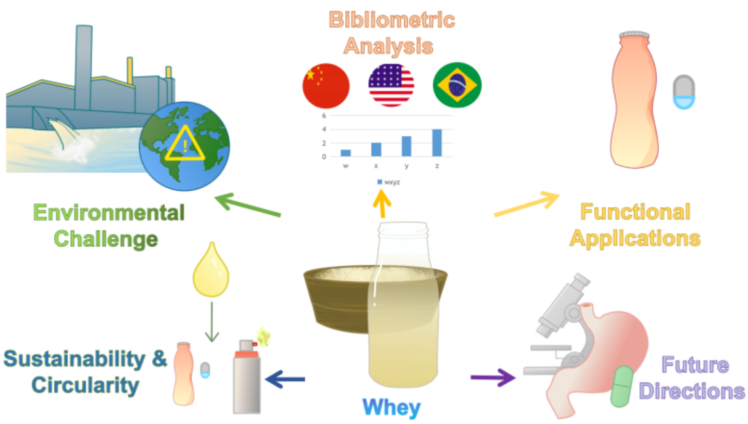
Abstract
Whey, a by-product of the dairy industry, poses significant environmental challenges due to its high organic load when improperly disposed of. This study aimed to analyze the scientific production of whey utilization in the food industry through bibliometric indicators and knowledge mapping to identify trends, emerging applications, innovations, and gaps in the literature. A bibliometric analysis was conducted using the Web of Science® database, with data processed via the Bibliometrix package in R. The results revealed a sustained growth in scientific output from 2004 to 2024, with an annual growth rate of 15.82%, highlighting China, the USA, and Brazil as leading contributors. Key research areas include whey's functional properties, applications in encapsulation technologies, emulsion stability, and bioactive peptide production with antioxidant, antimicrobial, and antihypertensive properties. Additionally, whey's role in sustainability is underscored by its potential in biogas and biopolymer production and its applications in human and animal nutrition, aligning with circular economy principles. The study concludes that whey's versatility as a functional ingredient and its potential in sustainable applications drive research growth. Future investigations should focus on optimizing biotechnological processes to enhance whey's functionality, reduce environmental impact, and explore its nutraceutical potential, mainly through clinical studies validating the health benefits of bioactive peptides derived from whey.

Keywords: Bioactive Peptides. Encapsulation Technologies. Anaerobic Digestion. Protein Hydrolysates. Circular Bioeconomy.

Resumo
O soro de leite, subproduto da indústria laticinista, apresenta desafios ambientais significativos devido à sua elevada carga orgânica quando descartado de forma inadequada. Este estudo teve como objetivo analisar a produção científica sobre a utilização do soro de leite na indústria alimentícia por meio de indicadores bibliométricos e mapeamento do conhecimento, a fim de identificar tendências, aplicações emergentes, inovações e lacunas na literatura. Foi realizada uma análise bibliométrica com dados extraídos da base Web of Science®, processados com o pacote Bibliometrix no software R. Os resultados revelaram um crescimento contínuo da produção científica entre 2004 e 2024, com uma taxa média anual de crescimento de 15,82%, destacando-se a China, os Estados Unidos e o Brasil como principais países contribuidores. As principais áreas de pesquisa incluem as propriedades funcionais do soro, suas aplicações em tecnologias de encapsulamento, estabilidade de emulsões e produção de peptídeos bioativos com propriedades antioxidantes, antimicrobianas e anti-hipertensivas. Ademais, o papel do soro na sustentabilidade é evidenciado por seu potencial na produção de biogás e biopolímeros, bem como em aplicações na nutrição humana e animal, em consonância com os princípios da economia circular. Conclui-se que a versatilidade do soro como ingrediente funcional e seu potencial em aplicações sustentáveis impulsionam o crescimento das pesquisas. Investigações futuras devem concentrar-se na otimização de processos biotecnológicos para ampliar a funcionalidade do soro, reduzir seu impacto ambiental e explorar seu potencial nutracêutico, principalmente por meio de estudos clínicos que validem os benefícios à saúde dos peptídeos bioativos derivados do soro.

Palavras-chave: Peptídeos Bioativos. Tecnologias de Encapsulamento. Digestão Anaeróbia. Hidrolisados de Proteínas. Bioeconomia Circular.

Graphical Abstract



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ROYALDATASET

1. Introduction

Whey is a by-product of milk that is commonly regarded as one of the main waste materials of the dairy industry. It appears as a yellow-greenish liquid that drains off after the separation of curd during cheese production (Çelik, 2020). Depending on the coagulation method, whey can be classified as sweet or acid: sweet whey has a pH value between 6 and 7 and results from enzymatic casein coagulation in cheese making, whereas acid whey has a pH lower than 5 and is produced through lactic fermentation or the addition of organic acidic compounds (Lizárraga-Chaidez et al., 2023).

The estimated global annual production of whey is 10 billion tons, of which only 50% is processed in an environmentally safe and sustainable manner. Whey has a high organic waste load, including approximately 50% of dry matter relative to the total product (which mostly consists of lactose, accounting for up to 75% of the total dry matter) and at least 250 compounds, such as macro- and micronutrient nitrogenous components. It contains essential amino acids like valine, leucine, and isoleucine, as well as both animal-derived proteins, 14% of which are hydrolyzed products. In addition to its protein content, whey also contains lactose, fat, and mineral salts (Besediuk et al., 2024; Pineda-Quiroga et al., 2015).

Traditionally, whey was either discarded into water systems or fed to livestock due to a lack of practical applications (León-López et al., 2022). One of the main issues regarding whey disposal is its interference with biological wastewater treatment processes due to its high oxygen demand (Çelik, 2020). When whey is disposed of on land, it can alter the soil's physicochemical properties, disrupting the surrounding ecosystem (Ramos-Suárez et al., 2024). As a result, current regulations in various regions have required cheese producers to implement strategies to reduce whey waste or ensure its proper disposal. Given that the production of 1 kg of cheese generates around 9 kg of whey, effective management practices are essential to reduce the environmental burden and promote more sustainable cheese production (León-López et al., 2022).

Various applications for whey have been proposed in response to the need to reduce environmental impact and utilize industry by-products. The increasing demand for high-protein products has created opportunities for ventures centered on whey utilization. Its protein fraction is one of its most valuable attributes and is responsible for important functional properties such as solubility, viscosity, emulsification, and gelation, broadening its applications. Noteworthy uses today include the production of whey permeate, which is valuable in the food industry for applications such as chocolate and bakery products, dairy enhancement, and the extraction of pharmaceutical-grade lactose (O'Donoghue & Murphy, 2023).

Another promising application is biogas production, especially as an alternative for small-scale producers unable to invest in higher-value whey processing. Biogas is generated from organic waste through anaerobic digestion, resulting in a methane-rich gas that serves as a high-energy fuel (Cioablă et al., 2017; Rico et al., 2015). In this context, anaerobic digestion is ideal for processing whey into biogas, as it not only produces energy but also yields a stable by-product that can be used as fertilizer (Ramos-Suárez et al., 2024). Biogas can be used for thermal and electrical energy generation, similar to how natural gas or liquefied petroleum gas is utilized (Saetang & Tipnee, 2022).

In Mexico, the inadequate disposal of whey persists as a widespread challenge, particularly in key dairy-producing regions such as Jalisco, Coahuila, Tizayuca, the Valley of Mexico, Puebla, and Veracruz. The heterogeneity of cheese production, which spans from large-scale enterprises to small artisanal micro-companies, complicates the implementation of standardized by-product management practices, including whey disposal. One proposed strategy to mitigate this problem is the production of biogas from whey, which could serve as a sustainable alternative for energy generation while promoting circular economy practices. Estimates suggest that valorizing the total whey generated nationwide could increase biogas output by up to 96% and offset approximately 17.1 million tons of CO_2 annually, representing 32% of Mexico's total calculated emissions in 2019 (Arellano-García et al., 2024).

The recovery and utilization of by-products play an important role in achieving a more sustainable and efficient industrial food system. These strategies help reduce costs while enhancing overall production efficiency. Proper whey utilization allows the industry to engage in a circular economy by focusing on the reduction, reuse, and recycling of food waste (Tița et al., 2024).

Thus, one viable strategy for adding value to industrial waste is to promote the circular economy by generating raw materials useful across various sectors. This calls for research into waste treatment alternatives grounded in circular economy principles. Unlike the linear economy (based on production and consumption with waste as the end point) the circular economy seeks to recover economic value from initial products, save energy, and ensure economic, environmental, and social viability for industries (Matiacevich et al., 2022).

Based on the above considerations, the objective of this study was to analyze the scientific output on the use of whey in the food industry using bibliometric indicators and knowledge mapping in order to identify trends, emerging applications, and innovations, as well as to detect opportunities, challenges, and gaps in literature.

2. Methodology

2.1. Search Strategy

A search was conducted on the Web of Science (WoS) database using the "Advanced Search" option on February 4, 2025. For this purpose, the following logical function was used: 'TS=("whey" OR "whey protein" OR "whey-based" OR "dairy whey" OR "milk whey") AND ("food industry" OR "food products" OR "functional foods" OR "food development" OR "food processing") AND ("potential" OR "utilization" OR "applications" OR "innovation" OR "sustainability")'.

This search strategy enabled the retrieval of scientific publications containing terms related to whey and its derivatives in the title, abstract, or keywords, ensuring their relevance to the food industry.

2.2. Inclusion and Exclusion Criteria

To refine the search and provide thematic focus, only original peer-reviewed research articles published between 2004 and 2024 were included, explicitly excluding review articles, meta-analyses, book chapters, conference proceedings, early access records, and other non-original publications. However, it is important to note that Web of Science indexing occasionally classifies narrative or critical reviews as "Articles", especially in journals that combine both formats (*e.g.*, *Current Opinion* or *Advances in Colloid and Interface Science*). Consequently, a few highly cited reviews remained in the dataset, as Bibliometrix preserves the document type provided by WoS without further semantic discrimination. These records were retained for transparency and to reflect their bibliometric impact, but their presence is acknowledged as a methodological limitation. The articles retrieved through the search were downloaded in BibTeX format ("savedrecs.bib") using the "Full record" option in WoS. These files were stored for subsequent bibliometric analysis.

2.3. Data Processing and Analysis

Data analysis was performed using R software, version 4.3.3 (2024-02-29) "Angel Food Cake", on an x86_64-pc-linux-gnu (64-bit) platform running the Linux Mint 22 Wilma operating system, based on Ubuntu 24.04 Noble. The bibliometrix package, version 4.3.0, was used for data processing. The "savedrecs.bib" file was imported and processed in R using the functions provided by the bibliometrix package. This enabled the extraction of key metadata, analysis of scientific production trends, identification of the most influential authors and sources, and visualization of collaboration networks and term co-occurrence. The information obtained was used to characterize the current state of research on whey as a functional ingredient in the food industry, identifying emerging applications, innovations, and gaps in literature.

3. Results and Discussion

3.1. Scientific production from 2004 to 2024

Table 1 summarizes the leading bibliometric indicators obtained from the analysis of scientific production on the use of whey in the food industry. This scientific production has shown sustained growth over the past two decades (2004–2024), with an annual growth rate of 15.82% calculated using the Compound Annual Growth Rate (CAGR) formula, which relates the number of publications in the initial and final year of the analyzed period and computes the compounded rate of increase over the entire timeframe. This method smooths year-to-year fluctuations and provides a consistent estimate of the average yearly growth, offering a more robust interpretation of publication trends in bibliometric analyses. During the analyzed period, a total of 954 documents were identified and published across 256 different sources, reflecting a wide dissemination of knowledge in various journals and academic outlets. The average age of the papers is 5.72 years, suggesting that a significant portion of the analyzed literature is recent and therefore aligned with the current state of research. Additionally, the average number of citations per document is 27.9, highlighting the academic impact of these publications.

Regarding content, a total of 2,524 Keywords Plus terms and 2,698 authors' keywords were identified, indicating thematic diversity and the consolidation of specific terminology in whey research.

The authorship analysis reveals the involvement of 4,286 researchers in the production of these documents, although the number of single-authored articles is very low (12), indicating a strong tendency toward scientific collaboration. On average, each document has 5.85 co-authors, suggesting an interdisciplinary and collaborative approach within this field of study. Furthermore, international collaboration is significant, with 29.98% of the documents resulting from joint efforts between authors from different countries, underscoring the global relevance of the topic.

Finally, all analyzed documents correspond to scientific journal articles, ensuring that the bibliometric analysis was based solely on peer-reviewed publications, thus contributing to the robustness of the results. This overall outlook highlights the consolidation of whey research as a growing field, marked by high scientific output, notable international collaboration, and substantial academic impact, reinforcing its potential as a functional ingredient in the food industry.

Table 1 Summary of findings from the bibliometric analysis of studies related to the incorporation of whey in the food industry during the period 2004–2024

Description	Results
General Information on the Data	
Sources (Journals, Books, etc)	256
Documents	954
Annual growth rate (%)	15.82
Document average age (years)	5.72
Average citations per document	27.9
Document Contents	
Keywords Plus (ID)	2524
Author's Keywords (DE)	2698
Authors	
Authors	4286
Single-author documents	12
Author Collaboration	
Single-author document	12
Co-Authors per document	5.85
International collaboration (%)	29.98
Document Types	
Article	954

Fig. 1 presents a comprehensive bibliometric analysis of whey research in the food industry over the period 2004–2024. The analysis includes metrics that allow for the evaluation of the evolution and impact of this research field, taking into account annual publication output, geographic distribution of authors, the most relevant publication sources, the influence of scientific journals, and the thematic classification of articles in the Web of Science. These data provide an overview of the growth and diversification of whey-related research, as well as its positioning within the scientific community.

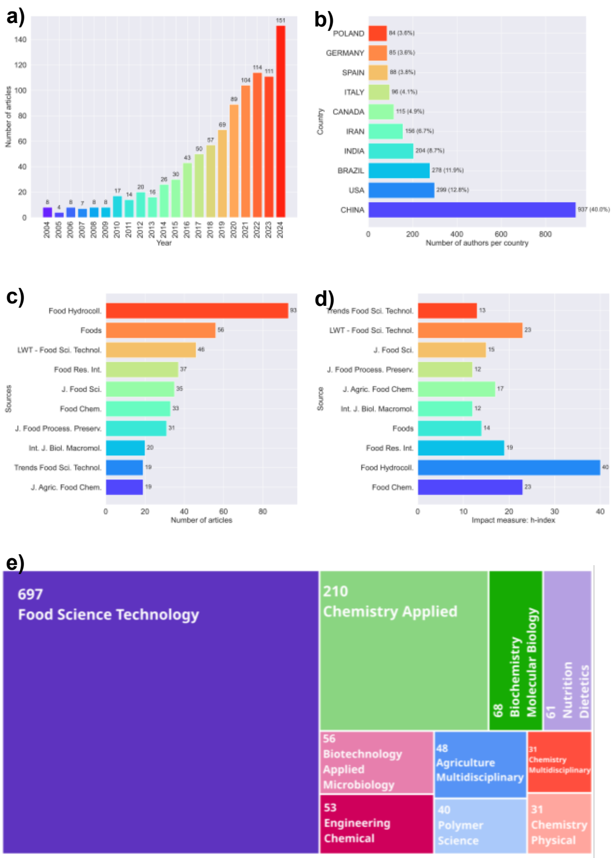

Fig. 1 Research metrics on the use of whey in the food industry (2004–2024): annual article production (a), geographical distribution of authors by country (b), leading publication journals (c), comparison of the influence of scientific journals based on their "h-index" (d), and research categories in Web of Science (e).

Fig. 1a illustrates the annual evolution of scientific publications on the use of whey in the food industry from 2004 to 2024. A gradual upward trend is evident, with limited activity during the initial phase from 2004 to 2010, when the annual output averaged fewer than ten documents. From 2011 onward, research activity expanded progressively, reflecting growing attention to whey as an ingredient with technological and nutritional potential. Between 2015 and 2019, the number of publications rose steadily from 30 to 69 per year, coinciding with a broader shift in the perception of whey from a dairy by-product to a valuable resource for sustainable food systems (Eberhardt et al., 2021; Zandona et al., 2021). This trajectory accelerated markedly after 2020, culminating in 151 publications in 2024, representing the highest annual output within the analyzed period.

Overall growth corresponds to an annual rate of 15.82%, calculated using the CAGR formula. This sustained rise aligns with a growing body of evidence recognizing whey's transition from an environmental liability to a versatile ingredient for functional foods and innovative food technologies. Whey retains up to 55% of milk's original nutrients while comprising most of the milk volume, making it an attractive substrate for valorization and product development (Eberhardt et al., 2021; A. F. Pires et al., 2021).

This expansion of research activity mirrors broader technological and economic developments. Studies have highlighted the diversification of whey applications, including its use in fermented beverages with sensory acceptability comparable to traditional yogurt while reducing production costs (Janiaski et al., 2016). The global whey protein market was valued at USD 10.65 billion in 2025 and is projected to reach approximately USD 22.95 billion by 2034, reflecting a strong trajectory of innovation and commercialization (Precedence Research, 2025). Parallel to market growth, academic research has increasingly addressed sustainability issues, exploring strategies for whey upcycling through fermentation to produce bioactive compounds or renewable energy (Malos et al., 2025; Rocha-Mendoza et al., 2021).

Therefore, the upward trend observed in **Fig. 1a** is not an isolated phenomenon but rather the result of converging factors: the recognition of whey's nutritional and functional properties, its economic potential within a circular economy framework, and the ongoing shift in research priorities toward sustainable food production (Zandona et al., 2021).

Fig. 1b presents the geographical distribution of scientific production on the use of whey in the food industry, highlighting the ten countries with the highest number of publications in this area. China leads the field with 937 publications (40.0% of the total), significantly outpacing other countries. This dominance suggests a strong interest from the Chinese scientific community in whey research and application, likely driven by the expansion of its dairy industry and the development of technologies for by-product valorization.

The United States and Brazil follow, with 299 (12.8%) and 278 publications (11.9%). Both countries possess robust dairy industries and research centers that actively drive innovation in functional foods, which may explain their prominent contributions to this field. In the United States, the University of California, Davis (UC Davis) hosts the Dairy Research Facility, which has recently explored the application of whey proteins in developing functional foods with enhanced nutritional and bioactive properties (Malos et al., 2025). Likewise, the University of Wisconsin–Madison's Center for Dairy Research focuses on advanced processing technologies and the extraction of bioactive peptides from whey for health-promoting applications (Malos et al., 2025). In Brazil, the Universidade de São Paulo (USP) investigates fermentation processes that utilize whey as a substrate for producing valuable metabolites, while Embrapa conducts studies on sustainable whey valorization and its integration into food technology to reduce dairy waste (Gianegitz et al., 2024; Malos et al., 2025). India, with 204 publications (8.7%), and Iran, with 156 publications (6.7%), have also demonstrated considerable scientific output, suggesting a growing interest in whey incorporation into developing new food products, particularly in regions where the demand for alternative proteins is increasing.

Canada (115 publications, 4.9%), Italy (96, 4.1%), Spain (88, 3.8%), Germany (85, 3.6%), and Poland (84, 3.6%) have maintained a consistent contribution. The presence of these countries underscores the importance of whey in the food industries of Europe and North America, where the valorization of dairy by-products is actively promoted within the framework of the circular economy and sustainability through initiatives that focus on reducing dairy waste and converting whey into high-value products such as bioactive peptides, bioplastics, and renewable energy (Almeida et al., 2023; Graça et al., 2022; Zandona et al., 2021).

Fig. 1c displays the main publication sources in the field. The journal with the highest number of published articles is *Food Hydrocolloids*, with 93 documents, indicating a focus on the functionality and structural applications of whey in food matrices, especially in terms of stability and rheological properties.

Foods (56 articles) and *LWT – Food Science and Technology* (46 articles) follow, both broad-scope journals in food science and technology, suggesting that whey research has been integrated into general studies on food development and processing. *Food Research International* (37 articles) and *Journal of Food Science* (35 articles) further reinforce the relevance of the topic in the context of food innovation.

Other notable sources include *Food Chemistry* (33 articles), reflecting interest in the physicochemical and functional characterization of whey, and *Journal of Food Processing and Preservation* (31 articles), which highlights its role in food preservation and stability. Although less prominent, journals such as *International Journal of Biological Macromolecules* (20 articles), *Journal of Agricultural and Food Chemistry* (19), and *Trends in Food Science & Technology* (19) show a focus on biochemistry, agro-industrial applications, and emerging trends in food technology.

Fig. 1d presents the impact of the main publication sources on whey research in the food industry, assessed using the h-index, which measures both the productivity and impact of a source's publications. While the bibliometric analysis included additional metrics, such as the g-index (which emphasizes the citation count of the most influential articles), the m-index (which adjusts the h-index based on the time since first publication), total citations, number of publications, and year of first publication (PY_start), the h-index remains the core measure.

The journal with the highest impact is *Food Hydrocolloids*, with an h-index of 40, indicating that at least 40 of its articles have received an equal or greater number of citations. It also exhibits the highest g-index (60), reflecting the strong citation performance of its most influential publications. With 3,994 total citations across 93 articles, *Food Hydrocolloids* stands as the leading reference source in whey research, particularly regarding its functionality in food matrices.

Food Chemistry and *LWT – Food Science and Technology* follow, both with an h-index of 23, though they differ in other metrics. Food Chemistry has accumulated 1,772 citations from 33 articles and began publishing on this topic in 2005, while

LWT – Food Science and Technology began in 2011 and has received 1,560 citations from 46 articles. The difference in their m-index values (1.533 for LWT *vs*. 1.095 for Food Chemistry) suggests that *LWT* has experienced faster impact growth relative to its publishing timeline.

Food Research International and Journal of Agricultural and Food Chemistry also stand out, with h-index values of 19 and 17, respectively. *Food Research International* has shown rapid recent growth (PY_start = 2014) with an m-index of 1.583, indicating increasing relevance. In contrast, *Journal of Agricultural and Food Chemistry*, with a longer publishing history (PY_start = 2005) and 1,190 total citations, has an m-index of 0.81, suggesting slower impact acceleration.

Among the sources with lower h-index values but notable thematic presence are *Foods* (h-index = 14, m-index = 2.0), *Trends in Food Science & Technology* (h-index = 13, m-index = 2.167), and *International Journal of Biological Macromolecules* (h-index = 12, m-index = 1.2). These journals have started publishing more recently (*Foods* in 2019 and *Trends in Food Science & Technology* in 2020) but have demonstrated growing influence in a short timeframe.

Finally, *Journal of Food Processing and Preservation* exhibits an h-index of 12 and an m-index of 1.0, with 31 publications and 518 total citations since 2014. Although its impact is not as high as other journals, its presence reinforces the relevance of whey in food preservation and processing.

Fig. 1e presents a tree map chart that visualizes the distribution of Web of Science categories within the scientific production on the use of whey in the food industry. This analysis helps identify the thematic areas where research has developed and the relative importance of each within the analyzed corpus.

The predominant category is Food Science Technology, with 697 records, representing 71.56% of the total documents. This indicates that most of the scientific output on the topic falls within the domain of food science and technology, which aligns with whey's application in the formulation and development of food products.

In second place is Chemistry Applied, with 210 records (21.56%), reflecting interest in the chemical and functional characterization of whey, including its composition, stability, and biochemical properties. Other categories with notable representation include Biochemistry Molecular Biology (68 records, 6.98%) and Nutrition Dietetics (61 records, 6.26%), indicating the relevance of whey in studies on metabolism, bioactivity of its components, and its role in human nutrition.

Categories such as Biotechnology Applied Microbiology (56 records, 5.75%) and Engineering Chemical (53 records, 5.44%) suggest a focus on fermentation, biotechnological processing, and innovations in whey valorization. Additionally, the presence of Agriculture Multidisciplinary (48 records, 4.92%) and Polymer Science (40 records, 4.11%) points to interest in agricultural applications and the development of biopolymers from whey.

Other less represented but relevant categories include Chemistry Multidisciplinary and Chemistry Physical, each with 31 records (3.18%), suggesting research on the molecular structure and interactions of whey with other components. Finally, the inclusion of categories such as Materials Science Multidisciplinary, Environmental Sciences, and Green Sustainable Science Technology highlights growing interest in the sustainable use of whey and its role in the circular economy.

This bibliometric analysis reveals a steady growth in scientific production related to whey, establishing it as an emerging area of interest in the food industry. Its versatility and functional potential have encouraged research across multiple disciplines, including food science and technology, applied chemistry, biotechnology, and nutrition. Moreover, the wide geographic distribution of publications and the impact of certain specialized journals suggest that this research area will continue to expand in the coming years. The revalorization of whey, driven by sustainability trends and circular economy principles, opens new opportunities for the development of innovative products and more efficient utilization strategies, positioning whey as a key resource in the formulation of functional foods and the optimization of food industry processes.

Table 2 presents the most frequently cited articles related to whey and its applications in the food industry, evaluated based on total citations, citations per year, and normalized citations. Not all of these studies are strictly aligned with the specific focus of the search query; however, they are widely cited within the field and reflect the broader scientific influence surrounding whey research. For clarity, **Table 2** also specifies the document type (original research or review), since some highly cited review articles appear among the top ten. Their inclusion underscores their relevance and impact despite not presenting original experimental data, which is recognized as a minor methodological limitation.

Table 2 Top 10 most cited publications retrieved from the search query on whey applications in the food industry and their bibliometric impact.

Reference	Journal	Total citations	Citations per Year	Normalized citations	Document Type
Qian et al. (2012)	Food Chemistry	393	28.07	5.59	Original research article
Liu & Tang (2013)	Journal of Agricultural and Food Chemistry	381	29.31	6.77	Original research article
Ozturk & McClements (2016)	Current Opinion in Food Science	347	34.7	4.92	Review article
Ye (2008)	International Journal of Food Science & Technology	290	16.11	4.56	Review article
Smetana et al. (2016)	Journal of Cleaner Production	274	27.4	3.88	Original research article (analytical and modeling study)
Wenten & Khoiruddin (2016)	Desalination	253	25.3	3.59	Review article
Smetana et al. (2019)	Resources, Conservation and Recycling	253	36.14	6.14	Original research article (analytical and modeling study)
Sah et al. (2016)	LWT - Food Science and Technology	231	23.1	3.27	Original research article
Simões et al. (2017)	Advances in Colloid and Interface Science	177	19.67	3.49	Review article
Vilcacundo et al. (2017)	Journal of Functional Foods	176	19.56	3.47	Original research article

The article by Qian et al. (2012), published in *Food Chemistry*, stands out as the most cited document in the present bibliometric investigation, with 393 citations and a rate of 28.07 citations per year. Its impact lies in the study of oil-in-water nanoemulsions stabilized with β-lactoglobulin as an encapsulation system to improve the stability of β-carotene, a bioactive compound with low water solubility and high susceptibility to degradation. The results demonstrated that nanoemulsions stabilized with β-lactoglobulin provided greater resistance to the chemical degradation of β-carotene compared to those stabilized with nonionic surfactants such as Tween 20, due to the protein's antioxidant activity and its effect on reducing interfacial oxidation. However, the study also showed that the physical stability of the system depended on factors such as pH, ionic strength, and storage temperature, with a higher risk of aggregation at pH values near the protein's isoelectric point (pH 4–5) and at high NaCl concentrations (>200 mM). These findings have been instrumental in the development of bioactive compound delivery systems based on whey proteins, reinforcing the significance of whey in the formulation of functional foods and nutraceutical products. Although the study focused on a purified fraction of whey, its results have been widely cited for providing experimental evidence of its functionality in the design of encapsulation systems for bioactive compounds in food applications.

The study by Liu & Tang (2013), published in the *Journal of Agricultural and Food Chemistry*, is the second most cited, with 381 citations and an annual rate of 29.31 citations, underscoring its relevance in research on natural emulsifiers and their potential application in stabilizing food systems. This work explored the use of aggregated soy protein isolate (SPI) nanoparticles as Pickering-type stabilizers in oil-in-water emulsions, demonstrating that heat treatment and the selection of appropriate ionic conditions improved stability against coalescence and syneresis. At higher SPI concentrations, the formation of a structural network that entrapped oil droplets was observed, providing greater resistance to destabilization. The similarity of these aggregates to conventional Pickering stabilizers highlights their potential as functional alternatives in food formulations. Although the study focused on plant proteins, its findings are highly relevant to the development of colloidal systems based on dairy proteins such as whey, broadening the scope of their application in functional products and the food ingredients industry. The high citation rate of this article is due to its experimental contribution to the design of colloidal systems using proteins as the stabilizing solid phase, a growing field within the formulation of functional foods.

The article by Ozturk & McClements (2016), published in *Current Opinion in Food Science*, stands out for its high annual citation rate (34.7 citations per year), reflecting the growing interest in the development of natural emulsifiers for the food industry. This work reviewed advances in the identification and application of naturally derived emulsifiers, including proteins, polysaccharides, phospholipids, and saponins, with a focus on their capacity to form and stabilize emulsions under varying environmental conditions. The findings indicated that proteins, such as caseins and whey proteins, exhibit high interfacial activity due to their amphiphilic nature, while polysaccharides enhance stability by modifying viscosity. Moreover, the role of phospholipids, particularly lecithin, in emulsion formation was highlighted, albeit with limitations in long-term stability. The article emphasizes the importance of understanding molecular interactions and environmental factors that affect emulsion stability, providing key insights for the rational selection of natural emulsifiers in food, cosmetic, and pharmaceutical formulations, in alignment with the growing demand for clean-label products.

The study by (Smetana et al., 2019), published in *Resources, Conservation and Recycling*, presents the highest annual citation rate (36.14 citations per year), highlighting its impact in sustainability research and the utilization of by-products in the food industry. This work evaluated the production of *Hermetia illucens* biomass as an alternative protein source through life cycle assessment (LCA), comparing its environmental impact with that of other protein sources such as whey, chicken meat, and conventional protein concentrates. The results showed that insect production is significantly more sustainable than chicken and dairy products when food industry by-products are used as feed inputs, thereby reducing waste generation and lowering the environmental footprint. Nevertheless, its impact remains higher than that of plant proteins in terms of resource consumption. Additionally, the study emphasized that optimizing feed conversion efficiency and incorporating renewable energy sources are key strategies for improving the environmental viability of this alternative. These findings have direct implications for the sustainable reuse of whey, as its integration into insect feed could represent an innovative approach to waste reduction and the promotion of circular models in the food industry (Smetana et al., 2019).

The work by Ye (2008), published in the *International Journal of Food Science & Technology* (290 citations), and the study by Smetana et al. (2016) in the *Journal of Cleaner Production* (274 citations), further underscore the importance of whey in both food innovation and sustainable production strategies. In the former, the electrostatic complexation between dairy proteins and polysaccharides was explored, highlighting its potential to enhance functional properties such as solubility, interfacial stability, gel formation, and emulsification. These findings have driven the development of new ingredients and applications in dairy products, such as acidified beverages and microencapsulation systems (Ye, 2008). In the latter, a life cycle assessment (LCA) of insect production as an alternative protein source was conducted, comparing it with animal-derived proteins, including whey. The results indicated that insect-based products can be up to five times more sustainable than dairy and meat proteins when agro-industrial by-products are used as feed inputs. This suggests that reusing whey in insect farming could represent an innovative approach to reducing its environmental impact and promoting more circular production systems in the food industry (Smetana et al., 2016).

The study published in *LWT - Food Science and Technology* accumulated 231 citations, with an annual rate of 23.1 and a normalized citation impact of 3.27. It evaluated the enrichment of probiotic yogurt with fiber-rich pineapple peel powder, aiming to valorize fruit processing by-products as functional ingredients and adding this fiber source shortened fermentation time and maintained probiotic viability, while modifying textural and rheological properties by reducing firmness and storage modulus during refrigerated storage. A looser protein network structure promoted syneresis, yet provided dietary fiber benefits and prebiotic-like effects comparable to inulin. This work has been widely referenced for demonstrating how agro-industrial residues can enhance the nutritional profile of dairy matrices while supporting sustainability in product development (Sah et al., 2016).

The publication in *Desalination* reached 253 citations, averaging 25.3 citations per year with a normalized impact of 3.59. It examined advances, limitations, and prospects of reverse osmosis (RO) technology across multiple industries, including its application in dairy processing for whey concentration and purification. The discussion covered improvements in energy recovery, membrane materials, process design, and challenges such as fouling, operational costs, and water recovery efficiency. Its frequent citation reflects the relevance of RO as an enabling technology for resource recovery and water reuse in the dairy sector, particularly within circular economy models (Wenten & Khoiruddin, 2016).

The article in *Advances in Colloid and Interface Science* obtained 177 citations, with an annual rate of 19.67 and a normalized impact of 3.49. It provided an in-depth overview of micro- and nanoencapsulation systems based on bio-derived materials for food applications, focusing on bioactive compounds' protection, controlled release, and improved bioavailability. Various encapsulation matrices, including proteins and polysaccharides, were analyzed for their performance under *in vitro* digestion models and real food matrices. Although not centered exclusively on whey, its principles on encapsulation design have been applied extensively to whey protein-based delivery systems, which explains its continued relevance in functional food research (Simões et al., 2017).

The research published in the *Journal of Functional Foods* accumulated 176 citations, averaging 19.56 per year, with a normalized impact of 3.47. It investigated the generation of bioactive peptides from whey hydrolysates with angiotensin-converting enzyme (ACE) inhibitory properties relevant to blood pressure regulation. Specific peptide fractions were characterized and shown to exhibit vigorous ACE-inhibitory activity *in vitro*, supporting their potential use in functional foods and nutraceutical formulations for cardiovascular health. The consistent citation performance of this work highlights the growing interest in dairy-derived bioactive peptides for health-oriented food innovation (Vilcacundo et al., 2017).

These results reflect the multidisciplinary interest in whey-related research, encompassing areas such as food chemistry, processing technology, sustainability, and biochemical functionality. The diversity of journals in which these articles have been published suggests that the topic has attracted the attention of researchers in food science as well as related disciplines, establishing whey as a high-value resource in the food industry.

3.2. Analysis of authors' keywords

Fig. 2 presents an analysis of the authors' keywords, detailing research trends regarding whey utilization in the food industry by exploring the frequency and interrelationship of key terms. This analysis provides insights into the primary focus areas, emerging topics, and research opportunities within the field.

Fig. 2a displays a word cloud generated from the authors' keyword analysis, allowing for the identification of the most frequently used terms in the literature on whey utilization in the food industry. The most frequent terms reflect the main research areas and applications related to whey proteins. The most prominent terms are "stability" (137 occurrences) and "whey-protein" (136 occurrences), suggesting that a significant portion of research is focused on the stability of whey proteins and their functionality in various food systems. Similarly, "beta-lactoglobulin" (99 occurrences) and "whey" (98 occurrences) underscore the relevance of whey and its protein fractions in food formulation.

Other key terms include "functional-properties" (85 occurrences), "microencapsulation" (74 occurrences), and "encapsulation" (73 occurrences), indicating a strong interest in the application of whey in encapsulation technologies aimed at enhancing the stability and bioavailability of bioactive compounds. Likewise, terms such as "antioxidant activity" (54 occurrences), "oxidative stability" (44 occurrences), and "bioactive peptides" (31 occurrences) reflect the focus on the antioxidant and bioactive properties of whey-derived peptides. Regarding physicochemical characteristics, notable terms include "physicochemical properties" (67 occurrences), "emulsifying properties" (46 occurrences), "rheological properties" (40 occurrences), and "solubility" (32 occurrences), indicating the role of whey in emulsion stability and its behavior in complex food systems. Additionally, the presence of terms such as "oil" (46 occurrences), "temperature" (35 occurrences), and "digestion" (22 occurrences) suggests that the behavior of whey under various processing conditions and its impact on nutrient bioavailability has also been studied.

Fig. 2b presents a thematic map that classifies the main research areas related to whey utilization in the food industry based on their centrality (relevance within the field) and density (degree of topic development). This representation enables the identification of the most established, emerging, and specialized themes in scientific literature. In the upper-right quadrant (Motor Themes) are the most developed topics with high centrality, indicating that they are core to the discipline and exhibit strong interconnections with other areas. Notable topics in this group include "stability," "whey-protein," and "microencapsulation," suggesting that research on whey protein stability and its applications in encapsulation constitutes a key and high-impact area within the food industry. The lower-right quadrant (Basic Themes) includes terms such as "beta-lactoglobulin," "functional-properties," and "pH," which represent foundational concepts in whey research. These topics are essential for the characterization and application of whey proteins, particularly in relation to their functionality and behavior under various environmental conditions. The lower-left quadrant (Emerging or Declining Themes) features terms like "growth," "lactic-acid bacteria," and "cheese whey," indicating that research on whey fermentation and the use of lactic acid bacteria is either in an emerging stage or experiencing a decline within the field. This may signal opportunities for future investigations or a decreasing level of interest in these areas under the current research context. Finally, the upper-left quadrant (Niche Themes) comprises specialized topics with a high degree of development but lower connectivity to other areas of study. Terms such as "gelatin," "mechanical-properties," and "edible films" appear in this category, suggesting that the use of whey in edible film formation and mechanical property studies represents a well-developed niche, albeit with limited impact on the broader field of whey research.

Fig. 2c presents a network visualization based on the co-occurrence of author keywords in research on whey utilization in the food industry. The nodes represent key terms, while the connections indicate relationships between them. The network structure reveals distinct thematic clusters, each representing a group of closely related terms delineating this field's main research areas. These clusters are briefly introduced in the visualization but are explained in greater detail below, including their centrality, density, and the most representative keywords that define their conceptual scope.

I. **Cluster 1. "Whey" (Centrality: 4.222, Density: 14.535, Frequency: 855):** The cluster identified as "whey" (in red) focuses on studies related to whey in general terms. The most prominent keywords in this group include "whey" (98 occurrences), "milk" (57 occurrences), and "*in-vitro*" (40 occurrences), suggesting that a significant portion of the research is centered on the characterization of whey and its behavior in various experimental models. There is also a clear association with terms such as "enzymatic hydrolysis" and "bioactive peptides," indicating interest in the production of functional peptides derived from whey. This cluster exhibits high centrality, meaning it is strongly connected to other topics within the conceptual map. Its moderate density indicates that, although it is a well-established area, it remains in expansion with multiple research lines under development.

II. **Cluster 2. "Beta-lactoglobulin" (Centrality: 6.259, Density: 16.721, Frequency: 1749):** The "beta-lactoglobulin" cluster (in blue) is the most extensive and consolidated, with key terms such as "beta-lactoglobulin" (99 occurrences), "functional-properties" (85 occurrences), and "pH" (68 occurrences). Research in this area focuses on the characterization of β-lactoglobulin, one of the main whey proteins, and its role in the formulation of functional products. There is also a strong connection with terms like "antioxidant activity" (54 occurrences), "emulsifying properties" (46 occurrences), and "rheological properties" (40 occurrences), suggesting that β-lactoglobulin is studied in relation to its stability and technological applications in the food industry. The high centrality and density of this cluster indicate that it represents a mature and fundamental research line within whey studies

III. **Cluster 3. "Growth" (Centrality: 0.847, Density: 16.412, Frequency: 178):** The "growth" cluster (in green) focuses on the use of whey in fermentation and biotechnology processes. Prominent terms include "growth" (21 occurrences), "lactic-acid bacteria" (21 occurrences), and "cheese whey" (18 occurrences), indicating a relationship with the growth of lactic acid bacteria and the valorization of cheese whey. The term "fermentation" also appears within this group, suggesting that this research area is oriented toward biotechnological processes for the production of value-added compounds. Despite its low centrality, which indicates fewer connections with other clusters, its high density suggests it is a well-developed field within its specific context.

IV. **Cluster 4. "Stability" (Centrality: 5.145, Density: 16.810, Frequency: 1606):** The "stability" cluster (in purple) is related to the stability of whey proteins and their technological applications. The most relevant terms in this section include "stability" (137 occurrences), "whey-protein" (136 occurrences), and "microencapsulation" (74 occurrences), suggesting a focus on the use of whey in encapsulation systems to enhance its functionality. Other important terms include "physicochemical properties" (67 occurrences), "nanoparticles" (44 occurrences), and "oxidative stability" (44 occurrences), indicating a strong link to stabilization technologies for whey proteins and peptides. The high centrality and density of this cluster position it as a key topic in current whey research, with applications in both food formulation and controlled release of bioactive compounds.

V. **Cluster 5. "Gelatin" (Centrality: 0.482, Density: 17.216, Frequency):** The "gelatin" cluster (in yellow) represents a specialized topic related to the application of whey in the formulation of edible films and coatings. Terms such as "gelatin" (14 occurrences), "mechanical-properties" (13 occurrences), and "edible films" (11 occurrences) suggest that this research area is oriented toward the development of biodegradable and structural materials based on whey proteins. Despite its low centrality, indicating it is a more isolated topic within the broader research landscape, its high density suggests that it is a well-consolidated area within its niche. This implies that the study of whey in the production of edible films and biomaterials represents a research line with specific applications in food packaging and preservation.

The results shown in **Fig. 2** reveal that research on whey in the food industry is primarily focused on its stability, functionality, and advanced technological applications such as encapsulation and emulsification, highlighting its potential as a functional ingredient in the development of new products. The word cloud highlights key terms such as whey-protein, stability, and microencapsulation, while the thematic map confirms that these topics are highly developed. It also identifies emerging lines of research, such as fermentation and the use of cheese whey, which could represent new opportunities in food biotechnology. The network visualization reinforces these findings by showing that the most influential clusters, beta-lactoglobulin and stability, have high centrality and density, indicating that they are well-established areas. In contrast, other clusters such as growth and gelatin represent more specialized approaches with lower interconnection. Altogether, these results reflect the versatility of whey and its growing relevance in food innovation, consolidating it as a key ingredient in the development of functional and sustainable products.

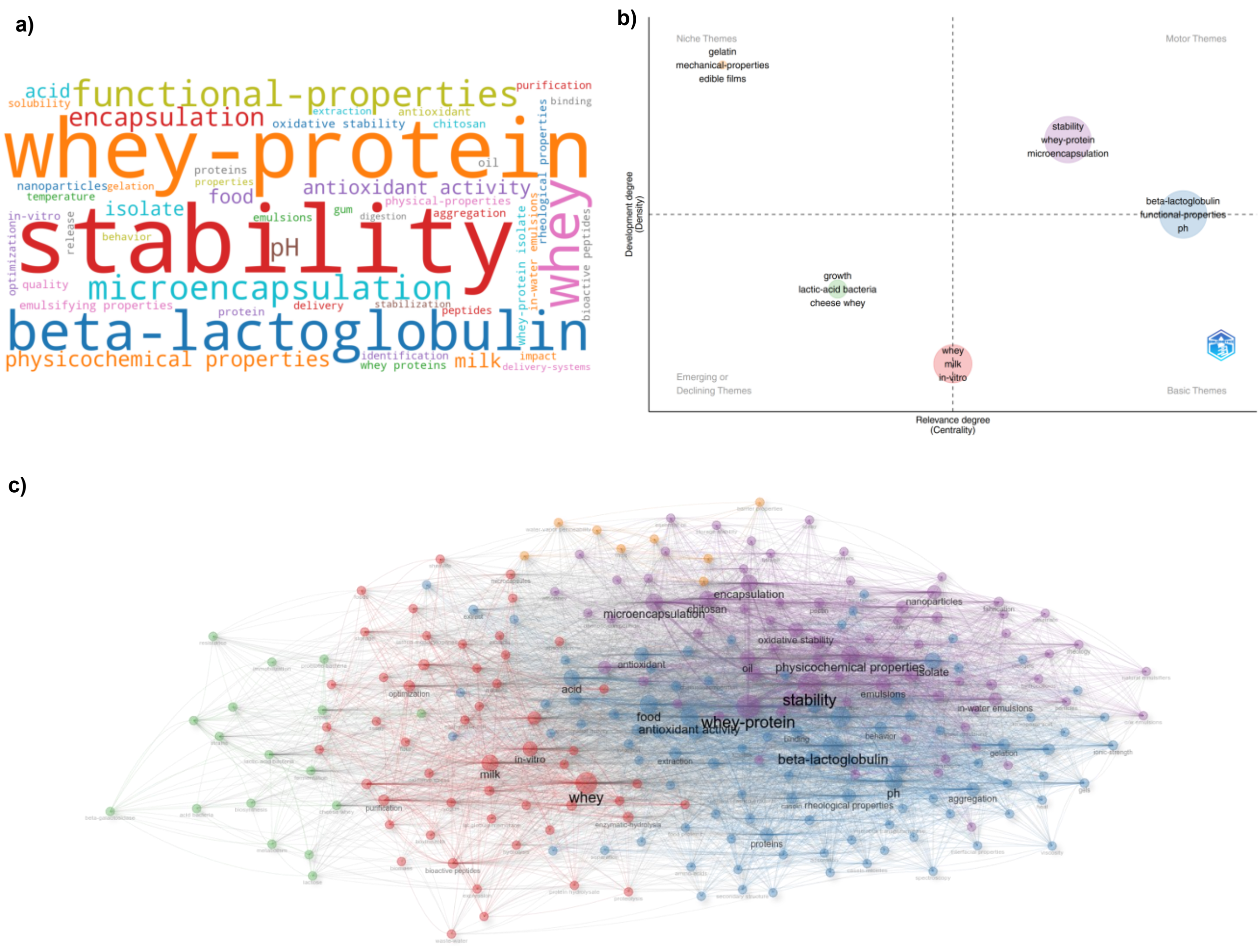

Fig. 2 Thematic analysis of research based on authors' keywords regarding the use of whey in the food industry. Word cloud highlighting the most recurrent terms in the literature (a). Thematic map classifying terms according to their centrality and density, identifying basic, motor, emerging, and niche topics within the research field (b). Network map of connections between terms, organized into main clusters representing specific research approaches (c).

Fig. 3 illustrates the evolution of key terms used in research on whey in the food industry from 2007 to 2024, highlighting emerging trends and shifts in the research focus over time. Although the dataset covered publications from 2004 to 2024, the visualization begins in 2007 because the keywords from 2004 to 2006 did not reach the minimum frequency threshold of five occurrences required by the Bibliometrix 'trendTopics()' function for inclusion (Nylas et al., 2024). This filtering procedure is a standard practice in bibliometric analyses to reduce noise and improve the interpretability of thematic trajectories, even though it may lead to the omission of years with low publication density or dispersed terminology (Aria & Cuccurullo, 2017). Each term is represented by a horizontal line indicating its temporal range of usage. At the same time, the size of the dots reflects the cumulative frequency of occurrences in the literature, with larger dots corresponding to terms appearing at least 100 times and smaller dots to those appearing at least 50 times during the analyzed period.

From a historical perspective, concepts such as “heat-induced gelation”, “nanofiltration”, and “kappa-carrageenan” appear in the early years of the analysis, suggesting that initial research was primarily focused on the physicochemical properties and processing techniques of whey. Subsequently, between 2012 and 2018, topics such as “fermentation”, “denaturation”, and “lactic-acid bacteria” gained relevance, indicating a growing interest in the biotechnological utilization of whey, particularly in fermentation processes and the production of bioactive compounds.

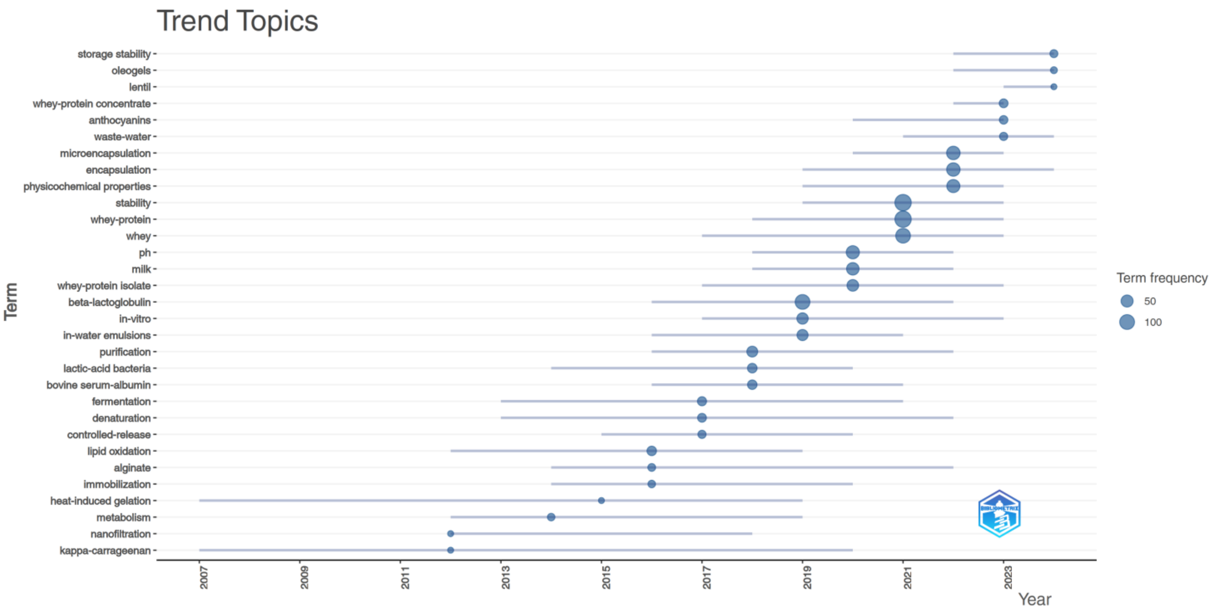

Fig. 3 Evolution of research topics on whey in the food industry (2007–2024): trends and frequency of key terms.

Since 2018, there has been a notable increase in the frequency of terms such as “beta-lactoglobulin”, “whey protein”, “stability”, and “physicochemical properties”, reflecting an emphasis on the characterization of whey proteins and their stability in food formulations. Additionally, terms like “microencapsulation” and “encapsulation”, which have emerged more strongly since 2020, suggest a growing body of research aimed at enhancing whey functionality through controlled release technologies and the protection of bioactive compounds.

More recent terms such as “whey protein concentrate”, “storage stability”, “oleogels”, and “lentil” point to new lines of research focused on whey stability in various food matrices and its potential application in alternative emulsification and product structuring systems. Altogether, this trend confirms the evolution of whey research from initial studies on processing and characterization toward more advanced applications in encapsulation, stability, and biotechnological exploitation, suggesting an increasing potential for its use in innovative formulations within the food industry.

Fig. 3 complements and expands upon the findings of **Fig. 2**, as both reflect the thematic evolution of whey research in the food industry but from different perspectives. While **Fig. 2** presents a co-occurrence analysis of terms and their organization into thematic clusters (**Fig. 2c**), as well as the relevance and density of research lines (**Fig. 2b**), **Fig. 3** offers insight into how these themes have evolved over time and which terms have gained prominence in recent years.

The main clusters identified in **Fig. 2c**, such as “whey protein”, “stability”, “microencapsulation”, and “beta-lactoglobulin”, also appear in **Fig. 3** with high frequency and sustained growth in recent years. This confirms that the stability of whey proteins and their technological applications, including microencapsulation and functionalization through emulsions and controlled release systems, have become established as key areas of research. Likewise, emerging terms in **Fig. 3**, such as “storage stability”, “oleogels”, and “whey protein concentrate”, suggest new directions that could lead to the formation of future clusters within the thematic network observed in **Fig. 2**.

Furthermore, the relationship between both figures is evidenced by the presence of terms related to fermentation and whey biotechnology. In **Fig. 2**, the “growth” cluster shows connections with terms such as “lactic-acid bacteria” and “cheese whey”, while **Fig. 4** shows that terms like “fermentation”, “lactic-acid bacteria”, and “bovine serum albumin” have undergone sustained development between 2013 and 2021, suggesting that this line of research has evolved and may be entering a phase of maturation.

Both figures reveal that whey research has shifted from a focus on characterization and stability toward more advanced applications in encapsulation, biotechnology, and functional formulations. While **Fig. 2** illustrates the structural organization of the research field and the interconnections between terms, **Fig. 3** enables the visualization of the temporal progression of these concepts, providing a more comprehensive perspective on the evolution and future trends in whey research within the food industry.

3.3. Factorial analysis approach

Fig. 4 presents a conceptual structure map generated through Multiple Correspondence Analysis (MCA), enabling the identification of relationships and proximity between the most relevant terms in whey research. This graphical representation aids in visualizing the distribution of concepts within the research field, grouping them according to their similarity and correlation in the two-dimensional space defined by the axes Dim1 (38.48%) and Dim2 (28.30%).

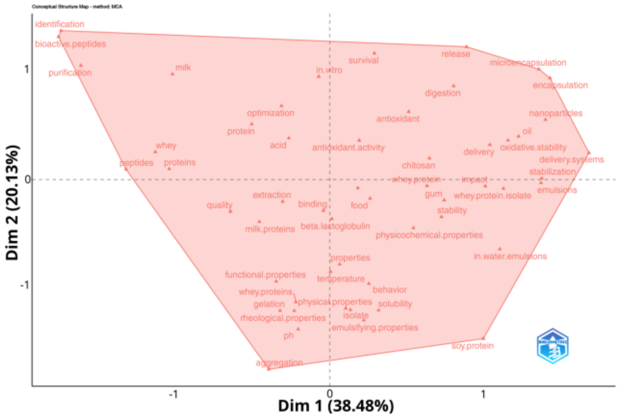

Fig. 4 Conceptual structure map of research on the use of whey in the food industry.

The terms located in the upper right quadrant of the map, such as "microencapsulation," "encapsulation," "nanoparticles," and "oxidative stability," reflect a cluster of concepts associated with whey functionalization and its application in encapsulation technologies and stabilization of bioactive compounds. The position of these terms suggests they represent well-established trends in current research.

In contrast, in the upper left quadrant, terms such as "identification," "bioactive peptides," and "purification" indicate a focus on the characterization and isolation of functional whey components, such as bioactive peptides with antioxidant and antimicrobial potential.

In the lower left section, terms such as "aggregation," "gelation," "functional properties," and "rheological properties" appear, suggesting a focus on the structural characterization of whey and its impact on textural and stability-related properties.

Meanwhile, in the central region of the map, terms such as "whey protein," "beta-lactoglobulin," "stability," and "physicochemical properties" cluster together, indicating that these concepts form the core of the research field, given their interaction with multiple thematic areas within whey research in the food industry.

Finally, the distribution of terms on the map confirms that whey research encompasses a broad spectrum of approaches, from the characterization of physicochemical properties to its application in encapsulation, stabilization, and functionalization. The observed structure suggests significant interconnection among these areas, reaffirming whey's versatility as a functional ingredient in the food industry.

4. Challenges in the research field

4.1. Sustainability and waste reduction

The valorization of by-products such as whey presents a wide range of challenges and opportunities for the dairy industry, particularly for the cheese production sector. One of the main challenges is the high organic load of whey, which contributes to environmental pollution when not properly disposed of. Whey exhibits high biological oxygen demand (BOD) and chemical oxygen demand (COD); thus, its disposal into water bodies is detrimental to aquatic ecosystems (Macwan et al., 2016; Rocha-Mendoza et al., 2021; Zotta et al., 2020). Furthermore, the type of product from which the whey originates influences its valorization potential. For instance, acid whey (a by-product of soft cheese production) contains high concentrations of lactic acid and has a low pH, increasing the challenges associated with its disposal (Murata et al., 2023; Rocha-Mendoza et al., 2021; Soumati et al., 2023; Wherry et al., 2019).

In response to these challenges, various strategies have been proposed to mitigate the environmental impact of whey disposal while simultaneously valorizing whey as a raw material. For example, anaerobic digestion, in which whey is converted into biogas, allows the generation of a renewable energy source while reducing methane emissions (Hallaji et al., 2019; Matassa et al., 2022).

Additionally, the recovery of valuable whey components such as proteins and lactose has underscored the sustainability benefits of this strategy. Techniques such as ultrafiltration and nanofiltration effectively separate these components, which can then be utilized in the food, pharmaceutical, and nutraceutical industries (Das et al., 2016; Mollea et al., 2013).

Furthermore, bioprocessing techniques have been explored to convert whey into functional beverages. For instance, fermentation of whey using specific cultures can yield health-beneficial beverages, such as yogurt enriched with probiotics (Tsimitri et al., 2021; Zokaityte et al., 2020).

Moreover, integrating whey into the production of biopolymers and other bioproducts represents another area of opportunity for whey valorization, contributing to the circular economy within the dairy industry (Asunis et al., 2024; Sinaga et al., 2023).

4.2. Whey processing and stability

One of the primary difficulties in removing contaminants from whey is the complexity of its composition, which includes lactose, proteins, minerals, and various low-molecular-weight compounds. The ultrafiltration process may retain undesirable compounds that affect the final product's quality (Corgneau et al., 2019). In addition, the presence of bioactive compounds and enzymes in whey can complicate purification, as these may interact with proteins and alter their functional properties (Guimarães et al., 2010).

The physicochemical stability of whey in food formulations is also influenced by several factors, such as pH, temperature, and the presence of other ingredients. For example, whey proteins typically denature when exposed to high temperatures, affecting the texture and stability of the final product (Rasouli et al., 2020). Heating whey above 70°C can impair its foaming properties, which are useful in various food applications (Musina, 2018). Similarly, interactions between whey proteins and components like calcium salts may cause colloidal instability, increasing viscosity and hindering heat transfer during processing (Barone et al., 2022). The formation of aggregates at low pH values is another significant stability concern, as it can lead to turbidity and undesirable sensory properties in whey-based beverages (Zamani et al., 2020).

To address these challenges, strategies such as the use of hydrocolloids and polysaccharides have been implemented to improve the stability of whey protein dispersions (Kaade et al., 2022; Rasouli et al., 2020). These additives can enhance the emulsifying and gelling properties of whey, broadening its application in various food products (J. Li & Zhu, 2024).

4.3. Regulations and standards

The incorporation of whey into various food products presents regulatory challenges that may impact its commercialization and innovation. One of the main barriers is its classification as a by-product of cheese manufacturing, which results in its undervaluation and limited use in food applications. Regulatory frameworks such as the Codex Alimentarius establish standards for milk and dairy derivatives; however, the diversity of regulations can hinder the implementation of whey in new formulations (Królczyk et al., 2016). In fact, the European Food Safety Authority (EFSA) has issued specific guidelines regarding the safety and composition of whey-based ingredients, requiring extensive safety studies before they can be marketed as novel ingredients (Ceniti et al., 2024).

Moreover, the allergenic potential of whey proteins, particularly α-lactalbumin and β-lactoglobulin, poses another challenge for their use and regulation (Yang et al., 2025). Food regulations typically require producers to demonstrate that their products meet safety standards, a process that can be long and costly, especially for small and medium-sized enterprises aiming to innovate with whey (Abitayeva et al., 2023).

Regulatory frameworks for whey-derived ingredients differ across regions. The European Union's requirements are more restrictive, particularly concerning labeling, permissible uses, and novel food approval pathways. In contrast, the United States applies a more permissive approach through the Food and Drug Administration (FDA), especially for substances with GRAS (Generally Recognized as Safe) status (Pereira et al., 2015). These regulatory asymmetries can complicate the international commercialization of whey-based formulations.

The environmental implications of whey disposal have prompted regulatory agencies to promote its use as an alternative in sustainability initiatives. Aligning with the Sustainable Development Goals and the circular economy concept may facilitate regulatory approval (Barba, 2021).

4.4. Consumer acceptance and perception

Consumer acceptance of whey-based products presents several challenges, primarily related to sensory attributes, preferences, and awareness of health benefits. Flavor perception, in particular, is a major obstacle, as the acidity and astringency characteristic of whey-based beverages may be unappealing to consumers. Some studies even report a metallic taste as a reason for consumer dissatisfaction (Childs & Drake, 2010; Zhang et al., 2020). Additionally, the texture of such products is often perceived as undesirable or gritty, contributing to low acceptance (Karabegović et al., 2022). Many consumers are also unaware of the nutritional benefits of whey (Harwood & Drake, 2019).

To improve consumer perception and acceptance of whey-based products, the importance of communicating their functional health benefits has been emphasized. Educating consumers on the role of whey proteins in muscle synthesis, immune support, and antioxidant properties may enhance their willingness to consume these product (Bull et al., 2017; Solak & Akin, 2012). Furthermore, the development of flavored and fermented beverages has shown improvement in the sensory properties of whey-based drinks (Karabegović et al., 2022).

The versatility of whey as an ingredient in a wide range of foods may also help shift consumer perceptions. Highlighting its role in products such as protein bars, smoothies, and functional beverages can position whey-based products as desirable items rather than by-products of other processes (Antonialli et al., 2018). Additionally, studies on consumer preferences have demonstrated that taste tests and sensory acceptance evaluations can be effective in overcoming consumer prejudice (Keogh et al., 2019).

4.5. Innovation in food applications

The incorporation of whey into food products often presents technological challenges that prevent its full potential from being realized. For instance, whey's high salt content can lead to nutritional imbalances and undesirable flavor profiles. Therefore, desalting processes are necessary to improve the palatability and nutritional value of whey-based products (Khetsomphou et al., 2023).

In addition, the microbial load present in whey can pose safety concerns, necessitating innovative processing technologies such as high hydrostatic pressure and ultrasound treatments to reduce microbial counts while preserving the nutritional and organoleptic properties of the final products (Barba, 2021). Moreover, the functional properties of whey proteins can be influenced by their interactions with other ingredients, which may limit their effectiveness in certain applications, such as emulsification and gelation (Kristensen et al., 2021).

Despite these limitations, recent years have witnessed the development of a variety of new whey-based ingredients and formulations that capitalize on its nutritional and functional properties. For example, whey protein concentrates and isolates have been increasingly used due to their high protein content and ability to enhance texture and mouthfeel (Komeroski & Oliveira, 2023; Musina, 2018). Other innovations have focused on packaging, enabling the development of packaging with antioxidant properties that help extend shelf life (Pedro et al., 2023). Furthermore, the production of "edible packaging" with antimicrobial properties has also been achieved (Dinika & Utama, 2019).

Additionally, exploring whey as a carrier for bioactive compounds has gained momentum, with studies showing that whey protein-based delivery systems can effectively encapsulate and protect sensitive bioactive agents, enhancing their stability and release profiles in food applications (Jiang et al., 2024). The integration of whey into beverages such as "smoothies" has also been explored, where its emulsifying and foaming properties contribute to improved texture and sensory appeal (Espinosa et al., 2024). The innovative use of whey in food applications addresses sustainability concerns by reducing waste and enhancing various food products' nutritional profile and functional characteristics.

4.6. Costs and economic feasibility

The economic feasibility of whey valorization has presented several challenges, primarily related to process scalability, processing costs, and market competition. The use of whey is often associated with high processing costs, along with the need for appropriate technology to maximize its utilization. For example, products such as whey concentrates or isolates require complex processes like ultrafiltration and spray drying, which can be capital- and energy-intensive, making them nonviable for all producers (Evans et al., 2010; Panesar & Kennedy, 2012; Zandona et al., 2021). Furthermore, variability in whey composition affects product yield and quality ranges, further complicating economic feasibility (Birnbaum, 2018; Dallas et al., 2014).

Additionally, further research is needed for products derived from "acid whey", such as "lactobionic acid" or "biofuels", as their overall economic feasibility remains uncertain (Narala et al., 2022; Tesfaw, 2023). In comparison, proteins from sources such as soy or seeds are typically more affordable and readily available, which further hinders the promotion of whey proteins (Antonialli et al., 2018; Panghal et al., 2018).

When comparing the costs of whey with other sources of functional proteins, whey protein is generally more expensive due to the processing required to isolate and concentrate the proteins. For instance, whey protein concentrate typically contains between 34% and 89% protein and commands a higher price than plant-based proteins, which can be produced at lower costs due to less intensive processing requirements (El-Tanboly, 2017; Evans et al., 2010). The nutritional and functional attributes of whey proteins, including a complete amino acid profile and properties such as emulsification and foaming, enhance their value but also account for their relatively higher cost (Wang & Guo, 2014; Wherry et al., 2019). In contrast, plant proteins, while usually more economical, may lack some of the functional attributes provided by whey proteins, which may limit their application in specific food products (Evans et al., 2010; Yaşar & Bozdogan, 2018).

4.7. Research and technological development

Research into the functional and bioactive properties of whey has identified several gaps that warrant further exploration. One significant area of interest is the interaction of whey proteins with other food components, such as polysaccharides and polyphenols, which can influence their functional characteristics. For example, studies have shown that whey proteins can form complexes with "inulin", resulting in improved physicochemical properties and potential prebiotic effects (Guo et al., 2018; Ha et al., 2016). However, the specific mechanisms underlying these interactions and their implications for food formulation are not yet fully understood.

Furthermore, although whey proteins are recognized for their high nutritional value and health benefits, the effects of processing conditions, such as pH and temperature, on their functional properties and bioactivity are not fully clarified (Ghanimah & Ibrahim, 2018). This highlights the need for systematic studies to assess how such variables influence the functional attributes of whey proteins.

Additionally, peptides derived from whey proteins have demonstrated several health benefits, including antioxidant, antihypertensive, and antimicrobial properties (Mazorra-Manzano et al., 2020). Nevertheless, the bioavailability and efficacy of these peptides in human health require further clinical investigation. The existing literature suggests that whey proteins may enhance immune system defenses and potentially protect the body against chronic diseases (Solak & Akin, 2012).

Regarding clinical studies validating the health benefits of whey consumption, several investigations have been conducted. For instance, "whey protein supplementation" has been associated with improved recovery after resistance exercise and increased muscle protein synthesis (Patel, 2015). Clinical trials have also shown that whey protein may aid in weight management and improve metabolic health by influencing satiety and glucose metabolism (Patel, 2015; Solak & Akin, 2012).

The impact of whey protein on specific health conditions, such as cardiovascular disease and diabetes, has been documented, although the underlying mechanisms are not yet fully characterized (Patel, 2015). For example, whey-derived bioactive peptides have shown potential in reducing blood pressure and improving lipid profiles, but more extensive clinical trials are needed to confirm these effects and determine optimal dosages and the most appropriate whey protein forms for therapeutic use (Solak & Akin, 2012).

5. Opportunities in the field of study

5.1. Development of novel functional ingredients

Antioxidant activity is one of the most extensively studied properties of whey-derived peptides. Available research indicates that these peptides contain specific sulfur-containing amino acids or aromatic residues that are particularly effective in reacting with free radicals (Báez et al., 2021; Giblin et al., 2019).

Moreover, whey protein hydrolysates have demonstrated varying degrees of antioxidant activity, with some studies reporting up to 26% DPPH scavenging activity by peptides isolated from cheese whey (Martín-del-Campo et al., 2019). This suggests that whey proteins may be a valuable source of natural antioxidants that could help mitigate oxidative stress in humans.

In addition to their antioxidant properties, peptides have also exhibited antimicrobial activity, as they have been shown to inhibit the growth of pathogenic bacteria, thereby enhancing food safety and the shelf life of products containing them (Kęska et al., 2019; Kumar et al., 2021). The antimicrobial activity of whey proteins can be attributed to their ability to interact with microbial membranes, leading to cell lysis and death (Kęska et al., 2019).

The antihypertensive potential of whey-derived peptides is of significant interest. For instance, certain dipeptides obtained from whey proteins have been shown to exhibit ACE-inhibitory activity, which may contribute to the management of hypertension (Han et al., 2021). The antihypertensive effects of these peptides are especially relevant in the context of dietary interventions aimed at reducing the risk of cardiovascular diseases (Daliri et al., 2018; Han et al., 2021). Additionally, whey proteins have been associated with improved metabolic health, including enhanced glucose regulation and appetite suppression, further supporting their role in managing obesity and hypertension (Rigamonti et al., 2019; Ziolkowski et al., 2024).

Recent studies have expanded our understanding of the functional properties of whey peptides for human health. For example, research has identified novel peptides derived from goat and camel whey that exhibit anti-obesity and metabolic benefits, indicating that non-bovine sources of whey may also provide valuable bioactive compounds (Baba et al., 2021; Sansi et al., 2024). Furthermore, the use of fermentation processes to enhance the bioactivity of whey proteins has been explored, with findings suggesting that lactic acid bacteria can produce peptides with improved antioxidant and antihypertensive properties (Mazorra-Manzano et al., 2020). This highlights the potential for developing functional foods that leverage the health benefits of bioactive peptides derived from whey.

5.2. Applications in innovative food products

Whey has gained attention due to its potential for incorporation into innovative food products, particularly those with vegan formulations, functional beverages, or sports drinks. The versatility of whey proteins, rich in essential amino acids and bioactive peptides, makes whey an attractive ingredient for enhancing the nutritional functions or profile of various foods (Mitropoulou et al., 2022; Skryplonek et al., 2019).

In functional beverages, whey has been successfully integrated into probiotic drinks that provide hydration and health benefits associated with probiotics. Research indicates that whey promotes the growth of beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, which are crucial for gut health (Abitayeva et al., 2023; Skryplonek et al., 2019). Furthermore, whey-based beverages have been shown to maintain the viability of probiotic cultures during storage, ensuring their efficacy (Schoina et al., 2019).

However, the incorporation of whey into fermented or prebiotic-containing foods presents both benefits and challenges such as the influence of whey on the flavor and texture of foods. On the positive side, whey enhances the nutritional profile of fermented products by providing essential nutrients and improving sensory attributes (Sansi et al., 2024; Sharma et al., 2017). For example, whey can improve lactose digestibility and enhance the flavor and texture of fermented products, making them more appealing to consumers (Sharma et al., 2017). Additionally, whey proteins may act as protective agents for probiotic bacteria, aiding their survival under harsh gastrointestinal conditions (A. Pires et al., 2024).

One challenge, however, lies in whey's pH, which could affect the survival of probiotic strains as lower pH levels may reduce their viability (Irkin & Yalcin, 2017). Moreover, whey's high BOD and biochemical composition pose an environmental risk (Alves et al., 2018). The formulation of whey-based products must also consider consumer preferences and potential allergic responses, especially in plant-based formulations that may not align with all dietary restrictions (Devries & Phillips, 2015).

5.3. Advances in processing techniques

Recent advancements in the processing of whey fractions have significantly improved the purity and functionality of whey proteins. Microfiltration and ultrafiltration are at the forefront of these innovations. Microfiltration, which uses membranes with pore sizes ranging from 0.1 to 0.2 μm, effectively separates caseins from whey proteins, allowing for the recovery of high-purity whey proteins in the permeate (Reale et al., 2020; Tian et al., 2022). The development of polymeric membranes with enhanced configurations has increased the efficiency of these processes, allowing better retention of caseins while facilitating the passage of whey proteins (Carter et al., 2021). In addition, the integration of enzymatic treatments (such as composite enzymatic catalysis) has been shown to enhance filtration performance by reducing membrane fouling and increasing protein recovery rates (Wen-qiong et al., 2021).

Ultrafiltration remains a fundamental method for concentrating whey proteins, and recent studies have demonstrated its effectiveness in producing whey protein concentrates and isolates with high protein content (Pavoni et al., 2020; A. Pires et al., 2023). The application of diafiltration alongside ultrafiltration has also been explored to further improve the purity of whey protein fractions by removing low-molecular-weight contaminants (Pavoni et al., 2020). Furthermore, combining ultrafiltration with other techniques, such as nanofiltration, has been proposed to optimize the recovery of valuable whey components while maintaining their functional properties (Macedo et al., 2021).

Enzymatic hydrolysis is another innovative approach that significantly enhances the bioavailability of whey proteins. This process involves using specific enzymes to break down whey proteins into smaller peptides, which may improve absorption and functional properties (Bustamante et al., 2021; Faucher et al., 2022). For instance, hydrolyzed whey proteins have been shown to exhibit increased antioxidant activity and improved bioactive properties, which are beneficial for health-related applications (Bustamante et al., 2021). Optimizing hydrolysis conditions, including enzyme-to-substrate ratios and reaction times, has been crucial for maximizing the yield of bioactive peptides (Bustamante et al., 2021). Additionally, studies have indicated that the bioavailability of these peptides increases when subjected to enzymatic hydrolysis, making them more accessible for absorption in the gastrointestinal tract (Liu et al., 2023).

5.4. Sustainable approaches and circular economy

The use of whey in bioprocesses such as the production of bioplastics, biofuels, and biofertilizers has been explored. Converting whey into value-added products is key to sustainable practices in the dairy industry and aligns production with the principles of the circular economy. Various biotechnological approaches have been studied to transform whey into useful materials. For example, fermentation processes using specific bacterial cultures can produce lactic acid, which can subsequently be processed into biofertilizers or biostimulants that enhance soil health and crop productivity (Caballero et al., 2021; Zandona et al., 2021). Additionally, anaerobic digestion of whey can produce biogas (a renewable energy source) while allowing for nutrient recovery, which can support microalgal biomass production for subsequent conversion into biofuels and other high-value products (Almeida et al., 2023; Ryan & Walsh, 2016).

Likewise, the potential of whey as a raw material for bioplastic production has been emphasized. Multiple studies have demonstrated that whey proteins can create biodegradable polymers, offering an eco-friendly alternative to petroleum-based plastics (Chalermthai et al., 2019). This addresses waste management issues related to whey disposal and contributes to reducing plastic pollution by providing sustainable materials for various applications (Chalermthai et al., 2019; Zandona et al., 2021). Moreover, integrating whey into bioprocesses enhances sustainability and promotes economic viability by creating new markets and reducing waste disposal costs (Lappa et al., 2019).

Regarding the recycling of whey in animal feed, whey serves as a protein-rich source containing essential amino acids beneficial for livestock growth and health. Studies have shown that whey can enhance performance in various animals, including calves and poultry, by improving feed efficiency and promoting lean body mass gain (Kanza et al., 2017; Moura et al., 2019). Inclusion of whey in animal diets can also reduce feeding costs by replacing more expensive protein sources such as soybean meal (Eseceli, 2021). However, challenges remain in this practice, especially concerning whey quality and the potential presence of toxic minerals or pathogens that could impact animal health (Ahmadi et al., 2020). Appropriate processing and quality control measures are essential to mitigate these risks and ensure that whey is a safe and effective ingredient in animal nutrition.

5.5. Applications in the pharmaceutical and nutraceutical industries

Whey-based ingredients play a significant role in products such as infant formulas and nutritional supplements due to their rich nutritional profile and bioactive compounds. Whey protein is recognized for its high digestibility and content of amino acids like leucine, which is essential for muscle growth and metabolic health (Devries & Phillips, 2015; Patel, 2015). Additionally, whey proteins possess immunomodulatory properties that may help prevent infections and allergies in children (H. Li et al., 2023).

In dietary supplements, whey proteins are used to enhance health benefits, including weight management and muscle preservation during caloric restriction (Pal et al., 2010; Shertzer et al., 2011). The presence of bioactive peptides further extends their health benefits by exhibiting antimicrobial and anti-inflammatory properties (Solak & Akin, 2012).

Whey components, such as proteins, also act as adjuvants in managing metabolic and cardiovascular diseases. Whey protein supplementation has been shown to improve metabolic profiles by enhancing insulin sensitivity and reducing plasma insulin levels, key factors in managing type 2 diabetes and metabolic syndrome (Pal et al., 2010; Pal & Radavelli-Bagatini, 2013). Furthermore, the antioxidant properties of whey, due to its abundance of bioactive compounds such as peptides generated through fermentative hydrolysis, play a role in mitigating oxidative stress, a key factor in the development of metabolic disorders (Martino et al., 2023; Zeng et al., 2024).

Whey proteins have also been found to influence levels of gut hormones, which play a role in appetite regulation and energy metabolism (Pezeshki et al., 2015). This modulation of gut hormones may result in greater satiety and reduced caloric intake, supporting weight management efforts and reducing the risk of obesity-related diseases (Sousa et al., 2012).

5.6. Strengthening interdisciplinary research

Interdisciplinary collaboration among food science, biotechnology, and health sectors concerning the potential applications of whey and its derivatives has increased, as recognition grows regarding the ways this ingredient benefits both consumers and products. For example, the integration of food science and biotechnology has enabled innovation in whey utilization; through fermentation, it is possible to produce a functional food and bioactive compounds such as lactobionic acid, which offers antioxidant benefits with nutraceutical potential (Narala et al., 2022; Rocha-Mendoza et al., 2021).

In terms of consumer perception, the acceptance of whey-based products is influenced by various factors, including perceived health benefits and the sensory attributes of the products. Research indicates that consumers are increasingly seeking products that offer added health benefits, which aligns with whey's nutritional advantages (Sajdakowska et al., 2018). Additionally, the development of whey-based beverages enhanced with appealing flavors and suitable texture can improve consumer acceptance of such drinks (Salgado et al., 2023).

Multidisciplinary approaches have proven effective in enhancing consumer perception and market acceptance of whey-based products. Effective marketing strategies that emphasize the natural and health-promoting aspects of whey can help mitigate consumer neophobia and increase acceptance of these products. Moreover, the application of sensory evaluation methodologies during product development has been crucial in optimizing the sensory attributes of whey-based beverages, thereby increasing their market appeal (Castro et al., 2013).

Furthermore, collaboration between food scientists and marketing specialists is essential to address consumer concerns and preferences. Consumers' perceptions regarding health and quality significantly influence their purchasing decisions concerning dairy products (Sajdakowska et al., 2018). By integrating knowledge from consumer behavior studies with product development, stakeholders can create whey-based products that meet health standards and align with consumer preferences, ultimately leading to greater market acceptance (Byrne, 2020; Gärtner et al., 2024).

5.7. Impact on public health and nutrition

Whey protein has gained attention in recent years for its multifaceted role in improving gut health and modulating immune responses. Research indicates that whey proteins can improve the composition of the gut microbiota, which is essential for maintaining intestinal health (Feng et al., 2022; Zhou et al., 2023). In addition, whey proteins may act as prebiotics, promoting fermentation processes that lead to the production of short-chain fatty acids (Feng et al., 2022; Mazorra-Manzano et al., 2020). Furthermore, the modulation of gut microbiota by whey protein supports digestive health and plays a role in immunomodulation by enhancing host defense mechanisms against pathogens and inflammatory responses (Brimelow et al., 2017; Shan et al., 2024).

Moreover, the consumption of dairy whey proteins has been associated with benefits in weight and glucose control. Several studies have demonstrated that whey proteins can suppress appetite and reduce food intake, thereby further supporting weight management (Chungchunlam et al., 2015; Reimer et al., 2017). Regarding glucose control, whey proteins have shown the ability to improve glycemic response, particularly when consumed prior to meals (Avirineni et al., 2022; Pal et al., 2010). Additionally, the rapid digestion and absorption of whey proteins may result in a swift rise in plasma amino acid levels, which can enhance insulin sensitivity and promote better glucose metabolism (Nychyk et al., 2021; Pal et al., 2010). Overall, whey protein consumption appears to be a promising strategy to improve metabolic health, particularly among individuals with obesity or overweight.

6. Conclusions and perspectives

The bibliometric analysis conducted on the use of whey in the food industry reveals sustained growth in scientific output between 2004 and 2024, with an annual growth rate of 15.82%. China leads in the number of publications, followed by the United States and Brazil, reflecting the global interest in the valorization of this by-product. Emerging applications of whey focus on its functionality as a food ingredient, particularly in encapsulation technologies, emulsion stability, and the production of bioactive peptides with antioxidant, antimicrobial, and antihypertensive properties. Furthermore, the role of whey in sustainability is underscored by its potential in biogas and biopolymer production, as well as its use as a functional ingredient in human and animal nutrition, aligning with the principles of the circular economy.

Looking forward, this research area is expected to move toward optimizing biotechnological processes that enhance whey functionality and reduce its environmental impact. Opportunities are foreseen in the development of nutraceutical products, incorporation into innovative food matrices, and exploitation of its prebiotic potential for gut microbiota modulation. Additionally, it is crucial to deepen clinical studies that validate the health benefits of bioactive peptides derived from whey, as well as to explore new applications in the pharmaceutical industry and the design of sustainable materials, thereby strengthening whey's role in the global bioeconomy.

It is important to acknowledge a methodological limitation of this study. Despite applying refinement criteria in Web of Science to exclude secondary literature, the indexing system occasionally categorizes analytical or modeling studies as reviews, and vice versa. As a result, a small number of highly cited review articles remained in the dataset, particularly among the most influential publications. While this does not compromise the overall bibliometric trends, it may slightly overrepresent secondary literature in the citation impact analysis. Future studies could perform an additional manual screening to strictly remove reviews from the final dataset.

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Authors' Contributions

L. A. M. F.: Writing - Original Draft; J. G. P. F.: Writing - Review & Editing; L. G. C.: Conceptualization, Writing - Review & Editing; A. E. C. G.: Project administration; E. P. E.: Visualization; E. C. L.: Validation; L. G. G. O.: Visualization. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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