SHEEP WHEY VALORIZATION: TECHNOLOGICAL ADVANCES, FUNCTIONAL POTENTIAL, AND CIRCULAR ECONOMY PERSPECTIVES

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Abstract

Sheep's milk whey is one of the most significant by-products of dairy processing and is often regarded as waste, despite its considerable functional and nutraceutical potential. Recent advances in enzymatic hydrolysis, membrane filtration, and fractionation technologies have shifted the paradigm toward the production of high-value products such as functional beverages, nutraceuticals, protein isolates, and bioactive peptides. This review provides an overview of sheep whey valorization, with a particular focus on its biofunctional applications and sustainability implications. Special attention is given to closed-loop models, where the transformation of waste into health-promoting food innovations is emphasized. Challenges related to scalability, economic feasibility, and regulatory constraints are critically discussed as key barriers to large-scale industrial adoption. Ultimately, sheep whey valorization is aligned with sustainable development goals and offers significant opportunities for improving food system resilience and public health.

Key words: *Bioactive peptides, Circular economy, Functional foods, Membrane filtration, Sheep whey valorization*

INTRODUCTION

Sheep's milk whey represents one of the most underutilized by-products of the dairy industry, despite its remarkable nutritional composition and functional potential. Globally, whey represents nearly 50% of the total volume of milk used in cheese production, and it is often treated as a waste stream, contributing to environmental concerns due to its high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) [1,2]. When disposed of untreated, whey pollutes soil and aquatic ecosystems, however, when valorized, it can be transformed into a valuable source of proteins, bioactive peptides, lactose, and micronutrients [3,4].

Sheep whey differs significantly from bovine whey in both composition and functionality. It typically contains higher levels of proteins (6–7%), bioactive peptides, and minerals such as calcium and phosphorus compared with cow whey (3.5–4.0% proteins) [5]. These compositional advantages translate into superior technological and functional properties, making sheep whey a promising raw material for high-value products such as protein concentrates, isolates, functional beverages, and nutraceuticals [6]. In Mediterranean and Balkan countries, sheep and goat whey have been traditionally transformed into whey cheeses such as ricotta, urdă, manouri, mizithra, and anari, highlighting their long-standing role in regional food cultures [7,8].

From a technological standpoint, advances in membrane processing (ultrafiltration, nanofiltration, reverse osmosis) have enabled the efficient fractionation of whey proteins, lactose, and minerals [9]. These methods concentrate

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proteins into whey protein concentrates (WPC) or isolates (WPI), reduce lactose for fermentation substrates, and allow selective recovery of high-value components. In parallel, enzymatic hydrolysis has emerged as a powerful tool to release bioactive peptides with antioxidant, antihypertensive, antimicrobial, and immunomodulatory activities [10,11]. Such hydrolysates derived from sheep whey consistently show higher biological activity compared with bovine whey, underscoring its nutraceutical potential.

Fermentation represents another promising valorization pathway. Lactic acid bacteria and probiotic strains can transform sheep whey into synbiotic beverages, kefir-type drinks, or fermented dairy products enriched with prebiotics [12]. These innovations address consumer demands for functional foods while also reducing lactose content, expanding the market to lactose-intolerant populations. Furthermore, combining whey with fruit matrices (such as apple or pomegranate) enhances sensory acceptance and antioxidant activity [13].

The short shelf-life of whey cheeses and derived products remains a critical barrier. Strategies such as Modified Atmosphere Packaging (MAP) and incorporation of natural plant extracts (oregano, rosemary, green tea polyphenols) have demonstrated significant improvements in storage stability without compromising sensory attributes [14]. These approaches align with the increasing consumer preference for clean-label preservation methods.

In addition to food applications, whey proteins and derivatives have found uses in biodegradable films, edible coatings, and bio-based plastics, illustrating their potential role in circular economy models [15]. Classical works anticipated whey's multifunctionality decades ago, when it was already described as a potential ingredient for bakery, beverages, and animal feed [16]. Today, these pioneering visions are being revisited and modernized under the umbrella of sustainability and resource efficiency [17].

Despite these advances, large-scale valorization of sheep whey faces barriers related to economic feasibility, technological scalability, and regulatory frameworks. Small and medium-sized enterprises often lack the infrastructure for membrane processing or enzymatic hydrolysis at industrial scale, while the high investment costs limit adoption [18]. Moreover, regulatory approval for novel bioactive peptides or functional claims remains complex. Nonetheless, the integration of whey valorization into circular business models provides clear pathways for sustainable growth. These include linking whey utilization with renewable energy production (biogas through anaerobic digestion), creating nutraceutical ingredients, and developing functional dairy products that simultaneously promote public health and environmental protection [19].

Controversial aspects remain in the literature regarding the cost-effectiveness of different technologies, the variability in whey composition between species, and the scalability of functional beverage production. Some studies highlight the superior biological activities of sheep whey hydrolysates, while others point to challenges in standardization and reproducibility [20]. These debates underline the need for harmonized methodologies and pilot-scale validation.

The purpose of this paper is to review and synthesize the current state of knowledge on sheep whey valorization, with an emphasis on technological advances, biofunctional applications, and sustainability perspectives. By combining insights from recent reviews and experimental studies, the paper highlights opportunities and limitations in transforming sheep whey from an environmental burden into a key resource for the circular bioeconomy.

MATERIAL AND METHOD

In order to prepare this paper, an extensive review of the scientific literature was conducted on the topic of sheep whey valorization, technological processing, functional applications, and circular economy perspectives. Scientific papers and review articles were collected from internationally recognized databases such as ScienceDirect, PubMed, Web of Science, Scopus, MDPI Journals, and Google Scholar, using combinations of keywords including "sheep whey," "whey valorization," "bioactive peptides," "functional foods," "membrane filtration," "enzymatic hydrolysis," "fermentation," and "circular economy."

The inclusion criteria were as follows:
(a) peer-reviewed publications written in English;
(b) studies directly addressing the composition, processing technologies, biofunctional properties, or sustainable utilization of sheep whey;
(c) articles published mainly in the last three decades, with preference for recent works (2010–2025), while also considering classical references of historical importance.

Exclusion criteria included studies not related to sheep whey or its processing, duplicate records, non-scientific publications, or articles without accessible full text.

The selected literature was screened and grouped into five thematic categories: (i) compositional characteristics of sheep whey, (ii) membrane technologies for protein and lactose fractionation, (iii) enzymatic hydrolysis and bioactive peptide production, (iv) fermentation and functional product development, and (v) sustainability and circular economy approaches.

A qualitative synthesis of the findings was performed, aiming to identify convergences, divergences, technological opportunities, and research gaps. This methodological approach ensures reproducibility, transparency, and relevance, allowing a comprehensive overview of the current state of research in sheep whey valorization.

RESULTS

Compositional characteristics of whey across species

The chemical composition of whey is decisive for its nutritional and technological value. Sheep whey contains higher protein levels (6–7%) compared with bovine whey (3.5–4.0%) and goat whey (4.5–5.0%), as well as elevated calcium and phosphorus content [5,21,22]. This superior composition enhances its biofunctional potential, particularly after enzymatic hydrolysis, where peptides show antioxidant and antihypertensive activity [6,10,11].

Whey is further classified into sweet whey (SW) and acid whey (AW). SW, obtained through rennet coagulation, contains 6–10 g/L proteins and 46–52 g/L lactose, whereas AW, produced by lactic acid fermentation, has lower pH and increased mineral solubility [23–25]. Variability also arises from animal species, seasonal conditions, diet, and lactation stage [26–30].

Table 1. Comparative composition of whey from different dairy species

Parameter	Cow whey	Sheep whey	Goat whey	Buffalo whey
Protein (%)	3.5–4.0	6.0–7.0	4.5–5.0	4.0–4.5
Lactose (%)	4.5–5.0	4.0–4.5	4.5–5.0	5.0–5.2
Ash (%)	0.6–0.7	0.9–1.1	0.7–0.8	0.8–0.9
Calcium (mg/100 g)	45–55	60–70	50–55	55–65
Sources	[23], [24], [25]			

Membrane technologies for whey valorization

Membrane separation techniques are central to whey processing. Ultrafiltration (UF) yields WPC and WPI, nanofiltration (NF) enables lactose reduction with salt retention, while reverse osmosis (RO) concentrates solids via water removal [9,17,28]. Ion-exchange chromatography and advanced spray-drying further improve protein fractionation and product quality [29,30].

Table 2. Membrane processes applied to sheep whey

Process	Target Fraction	Advantages	Limitations
Ultrafiltration (UF)	Proteins (WPC, WPI)	High protein recovery, good functional properties	Membrane fouling, high energy cost
Nanofiltration (NF)	Lactose reduction, mineral retention	Produces lactose-reduced whey, permeates for fermentation	Selectivity varies with feed
Reverse Osmosis (RO)	Water removal, solids concentration	High efficiency, water recovery possible	Requires high pressure
Sources	[28], [29], [30]		

Enzymatic hydrolysis and bioactive peptide release

The enzymatic hydrolysis of sheep whey proteins generates bioactive peptides with multiple health-promoting activities, including antioxidant, antimicrobial, antihypertensive, and immunomodulatory effects [6,10,34]. Enzymes such as trypsin, pepsin, and alcalase have been widely applied, with sheep whey hydrolysates consistently showing stronger biological activities compared to bovine whey [11,35].

Recent studies highlight the radical-scavenging activity and angiotensin-converting enzyme (ACE) inhibition potential of sheep whey hydrolysates, supporting their application in antihypertensive nutraceuticals [36]. Advances in in silico peptide mapping tools further accelerate the discovery of novel bioactive sequences, enhancing the potential for functional food development [37].

Fermentation and functional product development

Sheep whey is an excellent substrate for fermentation with lactic acid bacteria and probiotic strains, enabling the production of functional beverages and synbiotic dairy products [12,38]. Ultrafiltration-derived concentrates of sheep whey have been fermented into kefir-like beverages enriched with probiotics and prebiotics, improving both functionality and consumer acceptance [39]. In addition, combining whey with fruit matrices such as apple, guava, or pomegranate enhances antioxidant activity and sensory properties, providing potential for niche functional products [40-42]. These approaches not only add value but also diversify market opportunities for whey-based beverages.

Traditional and novel valorization approaches

Sheep and goat whey have historically been used to produce whey cheeses such as ricotta (Italy), urdă (Romania), manouri and mizithra (Greece), and anari (Cyprus) [7,8,43]. These products highlight the long-standing cultural importance of whey valorization. Innovations in this area include fortification of ricotta-type cheeses with transglutaminase to enhance texture and functionality [44].

Table 3. Traditional whey cheeses produced from sheep/goat whey

Cheese (Region)	Milk/Whey Base	Processing Technique	Main Characteristics
Ricotta (Italy)	Whey of sheep, goat, cow or mixtures	Heating whey at 85–95 °C, often with acidification	Soft, mild, ~11–13% protein
Urda (Romania)	Mainly sheep/goat whey	Heating whey after cheese draining, sometimes with added milk	White, crumbly, high protein, Balkan product
Manouri (Greece)	Sheep/goat whey + added cream/milk	Heating with enrichment	Creamy texture, PDO, higher fat
Sources	[7,8,43]		

Shelf-life extension and sustainability strategies

Whey cheeses and derived products have limited shelf-life due to high moisture and microbial susceptibility. Recent studies demonstrated that Modified Atmosphere Packaging (MAP) combined with natural plant extracts (oregano, rosemary, green tea) significantly prolongs storage stability [14,37]. These approaches maintain sensory quality and address consumer demand for clean-label foods.

Sustainability and circular economy perspectives

Despite the promising applications, large-scale valorization of sheep whey remains limited due to high processing costs, lack of infrastructure in small and medium sized enterprises, and regulatory barriers [45]. Circular economy approaches emphasize closed-loop valorization systems, where by-products are continuously reintegrated into food production or energy cycles [46].

An overview of integrated strategies for whey valorization in a circular economy framework is shown in Figure 1, adapted from Soumati et al. [1].”

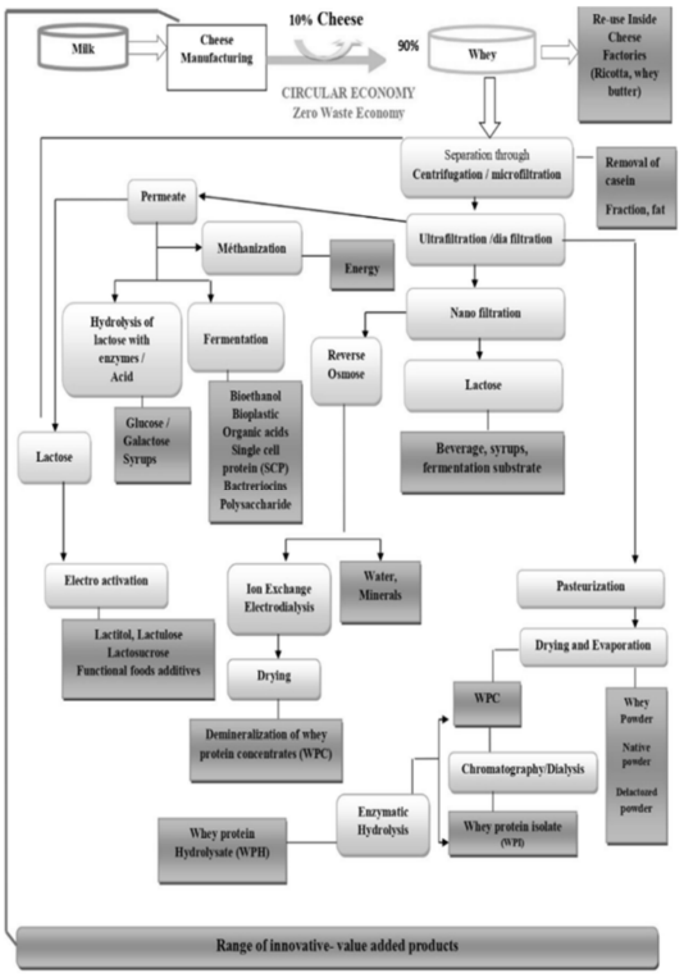

Fig. 1. Strategies and techniques for converting sheep whey into value-added products (adapted from Soumati et al. [1]).

Table 4. Shelf-life extension strategies for whey

Strategy	Mechanism	Effect on Shelf-Life	Advantages
Modified Atmosphere Packaging	Reduced O_2, elevated CO_2	Extends shelf-life by 5–10 days	Maintains freshness, slows microbial growth
Natural extracts (oregano, rosemary, green tea)	Antimicrobial & antioxidant	Extends 4–7 days vs. control	Clean-label, consumer friendly
Refrigerated storage (4 °C)	Slows microbial activity	7–10 days baseline	Simple, accessible
Sources	[14], [37]		

Sheep whey valorization integrated with renewable energy production (biogas via anaerobic digestion) provides environmental and economic benefits, while functional applications in nutraceuticals enhance public health outcomes [32,47]. Regional valorization strategies rooted in tradition (e.g., ricotta, urdă, manouri) serve as models of resilience, connecting cultural heritage with innovation [43].

Beyond technological and sustainability aspects, recent findings have further emphasized the distinctive biological roles of sheep milk proteins compared with bovine milk. Sheep proteins, particularly whey-derived fractions, exhibit superior immunomodulatory potential, antioxidant capacity, and anti-inflammatory effects, contributing to gastrointestinal health and chronic disease prevention [48].

Complementary comparative studies across cows, sheep, buffalo, and goats reinforce these perspectives, highlighting the higher protein concentrations and functional potential of sheep and buffalo whey [49]. Such biofunctional properties strengthen the argument for sheep whey valorization, not only as a technological challenge but also as a pathway for delivering advanced nutritional and therapeutic benefits.

DISCUSSIONS

The valorization of sheep whey has been consistently highlighted as a promising strategy for sustainable food innovation, yet challenges remain regarding its effective integration into industrial and nutritional systems. The present discussion interprets the results presented above in relation to existing literature, emphasizing convergences, discrepancies, and the broader implications for both science and practice.

Compositional aspects and functional implications

The higher protein and mineral content of sheep whey compared with bovine or caprine whey represents a key driver for its valorization [5,21]. Several studies have reported that sheep whey hydrolysates yield superior antioxidant and ACE-inhibitory activities, suggesting enhanced potential for nutraceutical applications [6,10,34]. These findings are consistent across different enzymatic treatments, confirming that protein richness directly correlates with bioactive peptide yield. However, variability in reported values remains a challenge: while Mohamed et al. [5] identified protein levels of 6–7%, other studies reported lower averages when analyzing mixed whey from blended milks [22]. This discrepancy underscores the need for more standardized analytical methods and species-specific data collection.

Membrane-based processing: opportunities and limitations

Membrane technologies remain at the core of whey valorization. Ultrafiltration is widely acknowledged for producing high-quality protein concentrates [9,17], yet membrane fouling and high operational costs continue to hinder scalability [26]. Nanofiltration and reverse osmosis provide additional avenues for lactose reduction and water recovery, supporting cleaner production models [26]. Comparative studies emphasize that while UF ensures strong protein recovery, NF and RO are essential for downstream applications such as fermentation and volume reduction [33]. Nevertheless, reported efficiencies vary depending on feed composition and operating parameters, revealing a gap between laboratory-scale data and industrial performance [17]. Future research should therefore focus on hybrid processing systems and anti-fouling membrane materials, aiming to bridge this gap.

Bioactive peptides and the need for clinical validation

One of the most consistent findings in the literature is the biofunctional richness of peptides derived from sheep whey [6,10,34]. Antioxidant and antihypertensive effects have been repeatedly confirmed in vitro and in silico models [36,37]. However, despite the abundance of biochemical evidence, there is a clear absence of large-scale clinical trials validating these effects in human populations. This represents a critical limitation, as regulatory approval for nutraceuticals and functional foods often depends on clinical substantiation [34]. While peptide databases such as that of Nielsen et al. [20] have expanded knowledge of potential bioactivities, translation into commercial health products remains limited. Therefore, interdisciplinary research linking dairy science, bioinformatics, and clinical nutrition is urgently required.

Fermentation and functional beverage development

Sheep whey has proven to be an excellent substrate for probiotic fermentation, resulting in kefir-like beverages and synbiotic formulations [12,33]. Studies combining sheep whey with fruit matrices (e.g., apple or pomegranate) demonstrated enhanced antioxidant potential and improved sensory acceptability [13,41]. These results align with broader consumer trends favoring natural and functional beverages. However, scalability is constrained by product stability and consumer familiarity. For instance, traditional whey beverages are well established in Mediterranean and Balkan diets [7,8], but their adaptation to global markets requires optimized preservation methods and targeted marketing strategies.

Traditional versus innovative valorization

A noteworthy aspect is the coexistence of traditional products, such as ricotta and urdă, with innovative applications like whey based films and bioplastics [7,15,42]. Traditional whey cheeses serve as cultural and nutritional benchmarks, yet their short shelf-life remains a critical limitation [14]. Novel technologies, including the use of transglutaminase for texture improvement [44], demonstrate how tradition can be combined with innovation. Furthermore, research on edible films and biodegradable packaging [20] provides an entirely new dimension to whey valorization, one that extends beyond food into environmental sustainability. This duality between preserving tradition and fostering innovation should be seen not as a conflict, but as a complementary pathway toward a more circular economy.

Shelf-life extension and sustainability approaches

Preservation strategies such as Modified Atmosphere Packaging (MAP) and natural bio-preservatives (oregano, rosemary, green tea extracts) have been shown to significantly extend the shelf-life of whey cheeses [37]. These findings are particularly important in addressing consumer demand for clean-label products while reducing food waste. However, limitations persist in terms of cost and potential flavor alterations. Despite these constraints, such approaches illustrate the potential for integrating food technology with sustainability goals, especially when combined with membrane processing and fermentation to optimize product stability.

Economic and circular economy perspectives

The integration of sheep whey valorization into circular business models remains challenging, particularly for small- and medium-sized enterprises (SMEs). High investment costs and technological complexity often prevent widespread adoption [18,39]. Nevertheless, case studies highlight that whey valorization can reduce environmental burdens while creating new economic opportunities, such as renewable energy generation via anaerobic digestion or the production of functional foods [12,39]. Soumati et al. [1] emphasized the potential of whey-derived products to support Sustainable Development Goals, particularly those related to responsible consumption and climate action.

This aligns with the notion that whey valorization is not solely a technological challenge, but also an economic and societal one.

Future directions

Based on the reviewed evidence, several directions for future research emerge.

First, there is a need for standardized compositional databases specific to sheep whey, separating it clearly from bovine and caprine data.

Second, technological innovations should target cost reduction and fouling resistance in membrane systems.

Third, interdisciplinary collaborations are required to validate bioactive peptide functionality through human trials. Finally, the integration of whey valorization into circular economy models should prioritize SMEs, ensuring that sustainability benefits are accessible across the dairy sector and not limited to large scale industries.

CONCLUSIONS

Sheep whey valorization represents a strategic pathway for advancing both scientific innovation and sustainable food systems. Its superior nutritional profile compared with other dairy species, coupled with technological advances in membrane separation, enzymatic hydrolysis, and fermentation, underscores its potential as a source of high-value functional ingredients and bioactive peptides.

Beyond nutritional and functional applications, integrated processing approaches, combining ultrafiltration, nanofiltration, enzymatic hydrolysis, and fermentation, enable efficient recovery of proteins, lactose, and micronutrients, while innovative preservation and packaging strategies extend product stability.

These advances align with circular economy principles by reducing waste streams and transforming whey into a valuable raw material for nutraceuticals, functional foods, and even non-food applications such as biodegradable films and bio-based plastics.

From a practical perspective, however, challenges remain. High processing costs, regulatory barriers, and scalability issues limit industrial adoption, particularly for small and medium-sized enterprises. Future progress will depend on bridging the gap between laboratory-scale evidence and commercial implementation, through standardized compositional databases, validated bioactivity in clinical trials, and the development of cost-effective, sustainable processing technologies.

Ultimately, sheep whey valorization is not merely a technological challenge but an opportunity to transform an underutilized by-product into a resource that supports public health, economic resilience, and environmental sustainability. By integrating tradition with innovation, and aligning with Sustainable Development Goals, sheep whey can be repositioned from an environmental burden into a key driver of circular bioeconomy growth.

REFERENCES

1. Soumati, B.; Atmani, M.; Benabderrahmane, A.; Benjelloun, M. Whey valorization – Innovative strategies for sustainable development and value-added product creation. *J. Ecol. Eng.* 2023, 24, 86–104. https://doi.org/10.12911/22998993/169505
2. Smithers, G.W. Whey and whey proteins – From 'gutter-to-gold'. *Int. Dairy J.* 2008, 18, 695–704. https://doi.org/10.1016/j.idairyj.2008.03.008
3. Besediuk, V.; Kosińska-Cagnazzo, A.; Zymon, M.; Zięba, T.; Kowalik, M.; Kowalczyk, D. Whey—From waste to a valuable resource. *Cleaner Chem. Eng.* 2024, 5, 100104. https://doi.org/10.1016/j.clce.2023.100104
4. FAO. Dairy Production and Products: Processing of whey. Food and Agriculture Organization of the United Nations, 2021. Available online: http://www.fao.org/dairy-production-products/processing/whey/en/ (accessed on 10 Sept 2025).
5. Mohamed, A.G.; Hassan, A.B.; Osman, N.M.; Ahmed, T.A. Sheep milk whey: Nutritional composition, functional properties, and nutraceutical potential. *J. Dairy Res. Technol.* 2023, 6, 19–25.
6. Sakkas, L.; Mavridis, I.; Stergiou, P.; Chasiotis, N.; Mallouchos, A. Whey protein hydrolysates of sheep and goat origin: Antioxidant, ACE-inhibitory and iron-chelating properties. *Foods 2022*, 11, 1947. https://doi.org/10.3390/foods11131947
7. Katsiari, M.C.; Voutsinas, L.P.; Alichanidis, E. Manufacture of traditional whey cheeses: A review. *Int. Dairy J.* 2002, 12, 719–735. https://doi.org/10.1016/S0958-6946(02)00055-9
8. Papademas, P.; Katsiari, M.C.; Voutsinas, L.P. Manufacture of whey cheeses (Manouri, Anari, Mizithra). *Int. J. Dairy Technol.* 1999, 52, 69–73. https://doi.org/10.1111/j.1471-0307.1999.tb01997.x
9. Zadow, J.G. Whey and lactose processing. *Elsevier Applied Food Science* Series, London, 1992.
10. Saubenova, M.; Abdrakhmanova, S.; Issayeva, A.; Mussakhanova, Z.; Nurgazezova, A. Bioactive peptides derived from whey proteins: Production, properties and applications. *Fermentation* 2024, 10, 359. https://doi.org/10.3390/fermentation10030359
11. Singh, N.; Kumar, R.; Mehta, S. Milk-derived bioactive peptides: New insights into functional properties and health benefits. Curr. Opin. *Food Sci.* 2024, 56, 101017. https://doi.org/10.1016/j.cofs.2024.101017
12. Guimarães, P.M.R.; Teixeira, J.A.; Domingues, L. Fermentation of lactose to bio-ethanol by yeasts as part of integrated solutions for the valorisation of cheese whey. *Biotechnol. Adv.* 2010, 28, 375–384. https://doi.org/10.1016/j.biotechadv.2010.02.002
13. Mangiapelo, L.; Cammalleri, C.; Alfeo, V.; Giosuè, C. Valorization of second cheese whey enriched with apple puree: Antioxidant properties and sensory profile. *Int. Dairy J.* 2025, 154, 105691. https://doi.org/10.1016/j.idairyj.2024.105691
14. Pappas, C.; Markaki, P.; et al. Effect of MAP and natural extracts on the shelf-life of whey cheeses. *LWT - Food Sci. Technol.* 2018, 98, 214–220. https://doi.org/10.1016/j.lwt.2018.08.025
15. Luparelli, A.; Caruso, M.; Romano, R.; De Pasquale, I. Whey proteins and bioactive peptides: From dairy waste to functional ingredients. *Foods* 2025, 14, 1123. https://doi.org/10.3390/foods14051123
16. Kosikowski, F.V. Whey utilization and whey products. *J. Dairy Sci.* 1979, 62, 1149–1160. https://doi.org/10.3168/jds.S0022-0302(79)83376-5
17. Buchanan, D. Recent advances in whey processing and valorisation: Opportunities and challenges. *Int. J. Dairy Technol.* 2023, 76, 456–469. https://doi.org/10.1111/1471-0307.12935
18. Mutio, C.; Kiiru, D.; Ouma, C.; Njogu, P.; Mwangi, J. Circular business models for whey valorization in the dairy sector. *Circ. Econ. Sustain.* 2025, 5, 112–128. https://doi.org/10.1007/s43615-02500491-6
19. Tița, M.A. Harnessing the potential of whey in the creation of innovative food products. *Recycling* 2024, 9, 79. https://doi.org/10.3390/recycling9010079
20. Nielsen, S.D.; Beverly, R.L.; Qu, Y.; Dallas, D.C. Milk bioactive peptide database: A comprehensive database of milk protein-derived bioactive peptides and novel visualization. *Food Chem.* 2017, 232, 673–

682. https://doi.org/10.1016/j.foodchem.2017.03.142
21. Hernández-Ledesma, B.; Ramos, M.; Gómez-Ruiz, J.Á. Bioactive components of ovine and caprine cheese whey. *Small Rumin. Res.* 2011, 101, 196–204. https://doi.org/10.1016/j.smallrumres.2011.09.021
22. Henriques, M.; Gomes, D.; Rodrigues, D.; et al. Performance of bovine and ovine liquid whey protein concentrate on functional properties of set yoghurts. *Procedia Food Sci.* 2011, 1, 2007–2014. https://doi.org/10.1016/j.profoo.2011.09.296
23. Rocha-Mendoza, D.; Kosmerl, E.; Krentz, A.; Zhang, L.; Badiger, S.; Miyagusuku-Cruzado, G.; Mayta-Apaza, A.; Giusti, M.; Jiménez-Flores, R.; García-Cano, I. Invited review: Acid whey trends and health benefits. *J. Dairy Sci.* 2021, 104, 1262–1275. https://doi.org/10.3168/jds.2020-19038
24. Ramos, O.L.; Pereira, R.N.; Rodrigues, R.M.; Teixeira, J.A.; Vicente, A.A.; Malcata, F.X. Whey and whey powders: Production and uses. *Encycl. Food Health* 2016, 498–505. https://doi.org/10.1016/B978-0-12-384947-2.00747-9
25. Papademas, P.; Kotsaki, P. Technological utilization of whey towards sustainable exploitation. *Adv. Dairy Res.* 2020, 7, 231. https://doi.org/10.35248/2329-888X.19.7.231
26. De La Fuente, M.A.; Hemar, Y.; Tamehana, M.; et al. Process-induced changes in whey proteins during the manufacture of whey protein concentrates. *Int. Dairy J.* 2002, 12, 361–374. https://doi.org/10.1016/S0958-6946(02)00027-4
27. Tsermoula, P.; Khakimov, B.; Nielsen, J.H.; Engelsen, S.B. Whey – The waste-stream that became more valuable than the food product. *Trends Food Sci. Technol.* 2021, 118, 230–241. https://doi.org/10.1016/j.tifs.2021.08.025
28. Panghal, A.; Patidar, R.; Jaglan, S.; Chhikara, N.; Khatkar, S.K.; Gat, Y.; Sindhu, N. Whey valorization: Current options and future scenario – A critical review. *Nutr. Food Sci.* 2018, 48, 520–535. https://doi.org/10.1108/NFS-01-2018-0017
29. Mollea, C.; Marmo, L.; Bosco, F. Valorisation of cheese whey, a by-product from the dairy industry. In: *Food Industry. IntechOpen*, 2013. https://doi.org/10.5772/53159
30. Sharma, R. Whey proteins in functional foods. In: *Whey Proteins. Academic Press*, 2019; pp. 637–663. https://doi.org/10.1016/B978-0-12-812124-5.00018-7
31. Dullius, A.; Goettert, M.I.; De Souza, C.F.V. Whey protein hydrolysates as a source of bioactive peptides for functional foods – Biotechnological facilitation of industrial scale-up. *J. Funct. Foods* 2018, 42, 58–74. https://doi.org/10.1016/j.jff.2017.12.063
32. Christensen, A.D.; Kádár, Z.; Oleskowicz-Popiel, P.; Thomsen, M.H. Production of bioethanol from organic whey using Kluyveromyces marxianus. *J. Ind. Microbiol. Biotechnol.* 2011, 38, 283–289. https://doi.org/10.1007/s10295-010-0770-1
33. Pires, A.; Ribeiro, C.; Gomes, A.; Pintado, M. Application of ultrafiltration to produce sheep's and goat's whey-based synbiotic kefir products. *Membranes* 2023, 13, 473. https://doi.org/10.3390/membranes13050473
34. Dinika, I.; Verma, D.K.; Balia, R.; et al. Potential of cheese whey bioactive proteins and peptides in the development of anti-microbial edible film composite: A review. *Trends Food Sci. Technol.* 2020, 103, 57–67. https://doi.org/10.1016/j.tifs.2020.06.009
35. Hernández-Ledesma, B.; Recio, I.; Amigo, L. Bioactive peptides in milk products: Minireview. *Int. Dairy J.* 2004, 14, 575–579. https://doi.org/10.1016/j.idairyj.2003.10.009
36. Yadav, L.; Bajwa, U. Valorization of cheese whey for sustainable production of functional ricotta-type cheese using transglutaminase enzyme. *J. Food Sci. Technol.* 2021, 58, 2527–2536. https://doi.org/10.1007/s13197-020-04786-2
37. Pappas, C.; Markaki, P.; et al. Effect of MAP (Modified Atmosphere Packaging) and natural extracts on the shelf-life of whey cheeses. *LWT - Food Sci. Technol.* 2018, 98, 214–220. https://doi.org/10.1016/j.lwt.2018.08.025
38. Asunis, F.; De Gioannis, G.; Dessì, P.; et al. The dairy biorefinery: integrating treatment processes for cheese whey valorisation. *J. Environ. Manage.* 2020, 276, 111240. https://doi.org/10.1016/j.jenvman.2020.111240
39. Asunis, F.; De Gioannis, G.; Francini, G.; et al. Environmental life cycle assessment of polyhydroxyalkanoates production from cheese whey. *Waste Manag.* 2021, 132, 31–43. https://doi.org/10.1016/j.wasman.2021.07.032

40. Chalermthai, B.; Giwa, A.; Schmidt, J.E.; Taher, H. Life cycle assessment of bioplastic production from whey protein obtained from dairy residues. *Bioresour. Technol. Rep.* 2021, 15, 100695. https://doi.org/10.1016/j.biteb.2021.100695
41. Costa, M.A.; Kuhn, D.; Rama, G.R.; Lehn, D.N.; Souza, C.F.V.D. Whey butter: a promising perspective for the dairy industry. *Braz. J. Food Technol*. 2022, 25, e2021088. https://doi.org/10.1590/1981-6723.10821
42. Chavan, R.; Kumar, A. Whey Based Beverage: Its Functionality, Formulations, Health Benefits and Applications. *Food Process. Technol.* 2015, 6, 1–7. https://doi.org/10.4172/2157-7110.1000456
43. Bintsis, T.; Papademas, P. Sustainable Approaches in Whey Cheese Production: A Review. *Dairy* 2023, 4, 249–270. https://doi.org/10.3390/dairy4020017
44. Deeth, H.; Bansal, N. Whey Proteins – An Overview. In: Whey Proteins. *Academic Press*, 2019; pp. 1–50. https://doi.org/10.1016/B978-0-12-812124-5.00001-1
45. Buchanan, D.; Martindale, W.; Romeih, E.; Hebishy, E. Review: Recent advances in whey processing and valorisation: Technological and environmental perspectives. *Int. J. Dairy Technol.* 2023, 76, 291–312. https://doi.org/10.1111/1471-0307.12935
46. Božanić, R.; Barukčić, I.; Lisak Jakopović, K.; Tratnik, L. Possibilities of Whey Utilisation. *Austin J. Nutr. Food Sci.* 2014, 2, 7.
47. Bosco, F.; Chiampo, F. Production of polyhydroxyalkanoates (PHAs) using milk whey and dairy wastewater activated sludge. *J. Biosci. Bioeng.* 2010, 109, 418–421. https://doi.org/10.1016/j.jbiosc.2009.10.017
48. Ben Fraj, S.; Enea, D.N.; Marin, M.; Vidu, L. The Biological Role of Sheep and Cow Milk Proteins. Sci. Pap. Ser. D. *Anim. Sci.* 2024, LXVII(2), 288–292. ISSN 2285-5750.
49. Scarlat, G.; Ștefan, A.-I.; Cîrîc, A.; Coman, Ș.; Vasiliu, R.E.; Pogurschi, E.N. Milk's Hidden Treasure: Exploring Whey Production in Cows, Sheep, Buffalo, and Goats. Scientific Papers. Series D. *Animal Science* 2025, LXVIII(1), 481–488. ISSN 2285-5750.