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Modern achievements and future prospects in membrane filtration technologies for acid whey valorization – an overview

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ABSTRACT

Acid whey is a by product obtained during the processing of fresh cheese like Jben (quark), regularly consumed in Morocco. It is generally perceived as an environmental challenge due to its substantial organic load and ecological impact, thus needing treatment before its elimination. However, it contains a valuable source of nutrients : proteins, lactose and minerals, that can be exploited for the creation and development of premium dairy innovations. This review aims to explore recent technological advances in membrane filtration, including ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), and their effectiveness in valorizing acid whey, while highlighting promising prospects for future development. The approach is based on a critical analysis of current scientific research, pilot trials, and industrial applications, emphasizing separation mechanisms, operating conditions, recovery rates, process efficiency, and the ability to isolate valuable functional fractions.Results demonstrate the notable efficiency of membrane processes: Ultrafiltration (UF) retains and concentrates more than 85% of total proteins. Nanofiltration (NF) enables the selective recovery of lactose with an efficiency of approximately 90%, while reverse osmosis (RO) recovers over 95% of clarified water, which can be reused in the dairy industry. Despite these benefits, certain challenges remain, such as membrane fouling and associated costs. Nevertheless, membrane filtration offers a promising alternative to convert waste into a valuable resource without additional chemical or biological treatments, supporting circular economy principles within the Moroccan dairy sector. Finally, this review highlights the main challenges and future outlooks essential for promoting the sustainable integration of membrane filtration technologies in the dairy industry.

Keywords: acid whey, membrane filtration technologies, functional fractions, high-value applications.

INTRODUCTION

The production of fresh cheeses, such as *Jben* populary consumed in Morocco generates substantial volumes of acid whey. This by product though rich in lactose, soluble proteins, and minerals, remains largely underutilized and is often treated as waste (Pires et al., 2021). Its high organic load presents both environmental and economic challenges for processing units especially when discharged without appropriate treatment (Valta et al., 2017). Given these challenges, the question of acid whey valorization has become ever more essential. Among existing technological solutions : membrane filtration stands out as one of the most promising approaches. Gentle, selective, and adaptable. This technology relies on semi-permeable membranes capable of separating whey components based on molecular size or specific physicochemical properties (Pouliot, 2008). Since the 1980s, it has gained wide adoption in the dairy industry, offering a spectrum of separation techniques such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Argenta and Scheer, 2020; Asad et al., 2020). Each technique presents unique advantages for the recovery of valuable compounds (Shekin, 2021). However, their full potential depends heavily on the choice of membrane materials, process configurations, and the ability to adapt to the specific characteristics of acid whey, which can vary with production conditions (Reig et al., 2021; Kumar et al., 2013).

Recent advances in membrane materials, modular designs, and integrated separation strategies have paved the way for more refined and targeted valorization of acid whey. Nonetheless, despite a growing body of research on the topic, there remains a lack of comprehensive and critical reviews that cross analyze technological performance, product quality, and industrial feasibility. This gap is particularly evident in the context of developing countries or regions with a strong cheese-making tradition such as Morocco, where solutions must be both efficient and locally adapted. This review seeks to address that gap. It distinguishes it self from existing literature through its integrated approach, connecting the fundamental principles of membrane separation with real-world industrial challenges. It aims to fill a void in the scientific discourse by evaluating actual performance outcomes of different technologies, identifying technical bottlenecks, and exploring the multifunctional potential of the resulting fractions (proteins, lactose, osmotic water). The primary objective of this review is to offer a critical and forward looking perspective on membrane technologies for acid whey valorization. Specifically, it aims to:

- Identify optimal operating conditions and the most suitable membrane configurations.
- Compare the performance of existing technologies across diverse industrial contexts.
- Highlight opportunities for improvement in membrane design and sustainability.
- Propose actionable research directions to transform this by-product into a high value resource, contributing to circular economy models and the sustainability of the dairy sector.

Through this approach, the review intends to close a critical knowledge gap and provide an original contribution to the understanding and optimization of acid whey valorization processes, with particular attention to the challenges and opportunities faced by emerging dairy industries, such as that of Morocco.

Membrane filtration – principles and mechanisms

Membrane filtration is a separation process based on the selective passage of components from a liquid solution through a semi-permeable barrier. This technology exploits various physical and physicochemical mechanisms: molecular size selectivity through a sieving effect, electrostatic repulsion based on charge known as the Donnan effect, and chemical affinity between solutes and the membrane surface, such as hydrophilicity or hydrophobicity. Thanks to this combination of mechanisms, it allows for fine separation without denaturing sensitive components (Lameloise, 2021; Asad et al., 2020):

- Through membrane filtration acid whey can be valorized into several functional fractions with high added value, following a sequential separation logic. Each membrane technology produces two distinct streams (Brião et al., 2024).
- The retentate: the fraction retained by the membrane, rich in targeted macromolecules or components.
- The permeate: the fraction passing through the membrane, composed of smaller or more soluble molecules.
- Four main techniques, classified by molecular weight cut-off, are currently used in the dairy industry (Mestawet et al., 2024; Nova et al., 2022; Wen-qiong et al., 2019).
- Microfiltration (MF) (0.1–10 µm) removes fat globules and bacteria; serves as an initial clarification step.(Mestawet et al., 2024).
- Ultrafiltration (UF) (1–100 kDa) retains serum proteins (β-lactoglobulin, α-lactalbumin), generating a protein-rich retentate RUF (Cuartas-Uribe et al., 2009).
- Nanofiltration (NF) (200–1.000 Da) concentrates lactose and divalent salts (Ca^{2+}, Mg^{2+}), producing an energy- and mineral-rich retentate RNF (Chandrapala et al., 2016).
- Reverse osmosis (RO) (< 1 nm) retains all solutes, providing an osmotic permeate (ROS), purified water reusable as process water (Subhir et al., 2022).

These techniques can be used individually or combined sequentially (MF → UF → NF → RO) or coupled with diafiltration to optimize the purity and functionality of the fractions (Chandrapala et al., 2016). This modular approach enhances process profitability and efficiency by allowing precise adjustment according to product goals.

Figure 1 illustrates this progressive separation of acid whey through the different membrane stages. To improve comparative clarity between these techniques, Table 1 provides a summary of the key characteristics of each process, their specific advantages, as well as examples of real industrial applications.

Novel membrane materials and designs

Responding to the increasing need for more effective and eco-friendly separation techniques, notable advancements have been achieved in the design of new membrane materials and sophisticated structural configurations specifically designed for the valorization of acid whey.

Organic membranes such as those made from polysulfone (PS), polyethersulfone (PES), cellulose acetate (CA), and polyvinylidene fluoride (PVDF) remain widely chosed due to their cost-effectiveness and adequate selectivity. However, their tendency to fouling particularly in protein limits effectiveness and necessitates frequent cleaning (Sathya et al., 2023; Kaur et al., 2020). To address these challenges, inorganic membranes especially ceramic membranes made from stable metal oxides such as : alumina Al_2O_3, zirconia ZrO_2, or titania TiO_2 have attracted growing attention. These materials offer exceptional thermal, mechanical, and chemical resistance, making them resistant to aggressive cleaning treatments without deterioration. Although their initial cost is higher, their prolonged durability and limited fouling issues make them a financially viable option for the long-term applications, particularly for microfiltration and ultrafiltration stages in the dairy industry (Mostafavi et al., 2019; Asad et al., 2020).

A new generation of membranes includes nanocomposites, which integrate inorganic nanoparticles such as silver (Ag), titanium dioxide (TiO_2), zinc oxide (ZnO), or graphene oxide (GO) into a polymer matrix. These modifications improve water affinity, antimicrobial properties and fouling tolerance, all of which are essential qualities for processing complex feed streams like acid whey (Yin et al., 2022; Kehinde et al., 2021).

In addition, thin film composite (TFC) membranes, commonly used in reverse osmosis and nanofiltration consist of a selective polyamide layer deposited on a porous support. These membranes are characterized by high solute rejection and high flux rates and are widely used for lactose concentration and water recovery (Saleh et al., 2025).

Membrane performance also depends on structural configuration. Asymmetric membranes, which include a dense selective layer over a porous sublayer, are designed to balance permeability and selectivity. Various module designs are selected based on the application:

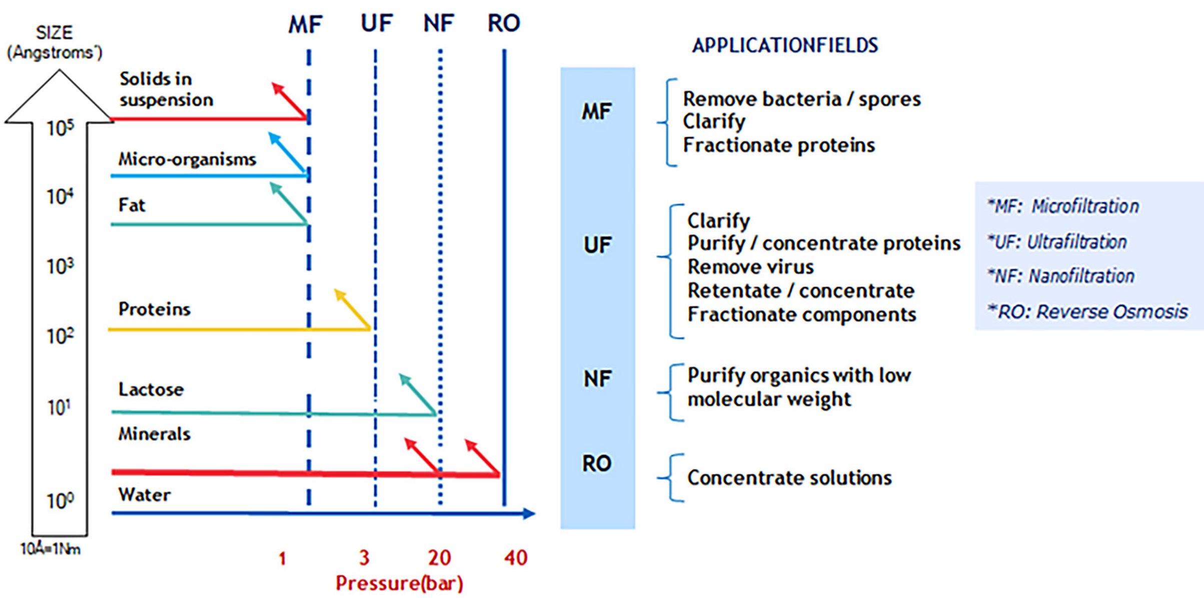

Figure 1. Sequential membrane filtration and separation mechanisms of whey components

Table 1. Comparative overview of membrane filtration processes for acid whey valorization: key parameters, applications, and selected studies

Membrane process	MWCO / pore size	Operating pressure	Typical temperature range	Fraction obtained	Typical use	Industrial or pilot example	Reference
MF (Microfiltration)	0.1–10 μm	0.1–2 bar	40–55 °C	Clarified whey (false retentate)	Clarification prior to UF or fermentation	Pre-treatment in cheese whey protein recovery	(Carter et al., 2021)
UF (Ultrafiltration)	1–100 kDa	2–6 bar	40–50 °C	RUF – high-protein retentate	Protein enrichment, WPC, infant formula	Pilot-scale WPC from acid whey (>90% protein retention)	(Macedo et al., 2012; Brião et al., 2024)
NF (Nanofiltration)	200–1.000 Da	4–30 bar	20–45 °C	RNF – lactose- and mineral-rich retentate	Lactose concentration, fermentation base	NF for lactose separation in acid whey plants	(Gésan-Guiziou et al., 2002; Minhalma et al., 2007)
RO (Reverse Osmosis)	<1 nm	20–60 bar	20–35 °C	ROS – purified water permeate	Water recovery, CIP, zero-discharge process	RO in acid whey processing for eco-efficient water reuse	(Chamberland et al., 2020; Marx et al., 2018)
Diafiltration (DF) (combined UF or NF)	Depends on base membrane	+1–2 bar above base pressure	Same as UF or NF	Enhanced purity of RUF or RNF	Lactose removal, demineralization, protein polishing	UF-DF for acid whey protein isolates	(Baldasso et al., 2022)

- spiral-wound modules are the most commonly used in industrial RO and NF due to their compact design and high membrane area

Tubular and hollow fiber modules are preferred for viscous solutions or those with suspended solids; flat-sheet modules are also used in laboratory testing or in applications requiring precise flow control (Das et al., 2022; Kumar et al., 2013).

Recent membrane innovations focus on bio-inspired designs and stimuli-responsive smart materials. Biomimetic membranes, incorporating aquaporins or synthetic analogues of ion channels, enable highly selective separation with low energy input. In parallel, smart membranes can adapt their separation behavior in response to environmental stimuli (pH, temperature, electric field), offering a major advantage for processing variable and complex matrices such as acid whey. Although these technologies are still at an early stage of industrial deployment, they represent promising solutions for precise separation with reduced energy consumption.Overall, the integration of innovative materials with strategic configurations continues to shape the future of membrane applications in acid whey valorization (Zan et al., 2025).

Table 2 summarizes the main membrane types, materials, structural configurations, key industrial applications, and their respective advantages in the context of acid whey processing.

Table 2. Overview of advanced membrane types, materials, structural characteristics, applications in acid whey fractionation

Membrane type	Material	Structure	Application step	Target components	Key advantages	References
UF	PES, PS, CA, PVDF	Asymmetric, flat/spiral	Protein concentration	Whey proteins	Moderate cost, good permeability	(Rektor et al.,2004); Bégoin et al., 2006)
UF	Ceramic (Al_2O_3, TiO_2, ZrO_2)	Tubular or monolithic	Protein concentration	Whey proteins	High stability, low fouling tendency	(Erdem et al.,2006); Carter et al., 2021)
NF	Thin-Film Composite (TFC, Polyamide)	Spiral-wound	Lactose/mineral concentration	Lactose, Ca^{2+}, Mg^{2+}	High selectivity, high yield	(Hartinger et al., 2019) Cuartas-Uribe et al., 2009)
RO	Polyamide TFC	Spiral-wound	Water purification	Water	High rejection rate, compact module design	(Shekin J, 2021); Madaeni & Mansourpanah, 2004)
UF/NF	Nanocomposite (e.g, TiO_2/GO + PES)	Flat sheet or spiral	Multi-step applications	Proteins, lactose, salts	Antifouling, improved hydrophilicity	(Chandrapala et al., 2016); Charcosset, 2021); Kehinde et al., 2021)
NF	PES/PA + MOFs (ZIF-8, MIL-101)	Flat sheet / spiral	Lactose & mineral separation	Lactose, Ca^{2+}, PO_4^{3-}	High selectivity, anti-fouling	(Talebi et al., 2020); Bégoin et al., 2006); Mestawet et al., 2024)

Figure 2 presents representative images of organic and inorganic membranes illustrating their structural design.

Advanced process configurations

Recent advances in membrane filtration applied to the recovery of acid whey highlight the need for innovative process layouts that maximize separation performance and improve the functional quality of the resulting streams. Within this context, diafiltration has emerged as a key method, widely studied for its capacity to increase protein purity by washing away small molecules like lactose and certain salts from the retained material. The approach relies on the stepwise addition of water-or other appropriate solvents-during filtration, allowing undesirable solutes to exit while larger proteins remain in place.

Research by (Rosseto et al., 2024) has demonstrated that diafiltration can significantly increase the protein concentration in the ultrafiltered retentate (RUF) while substantially reducing lactose content, thereby enabling the production of ingredients adapted to specific nutritional requirements such as low-lactose or high-protein diets. In addition, diafiltration positively influences protein functionalities by enhancing solubility and emulsifying properties, which are essential for their successful incorporation into a wide range of food formulations.

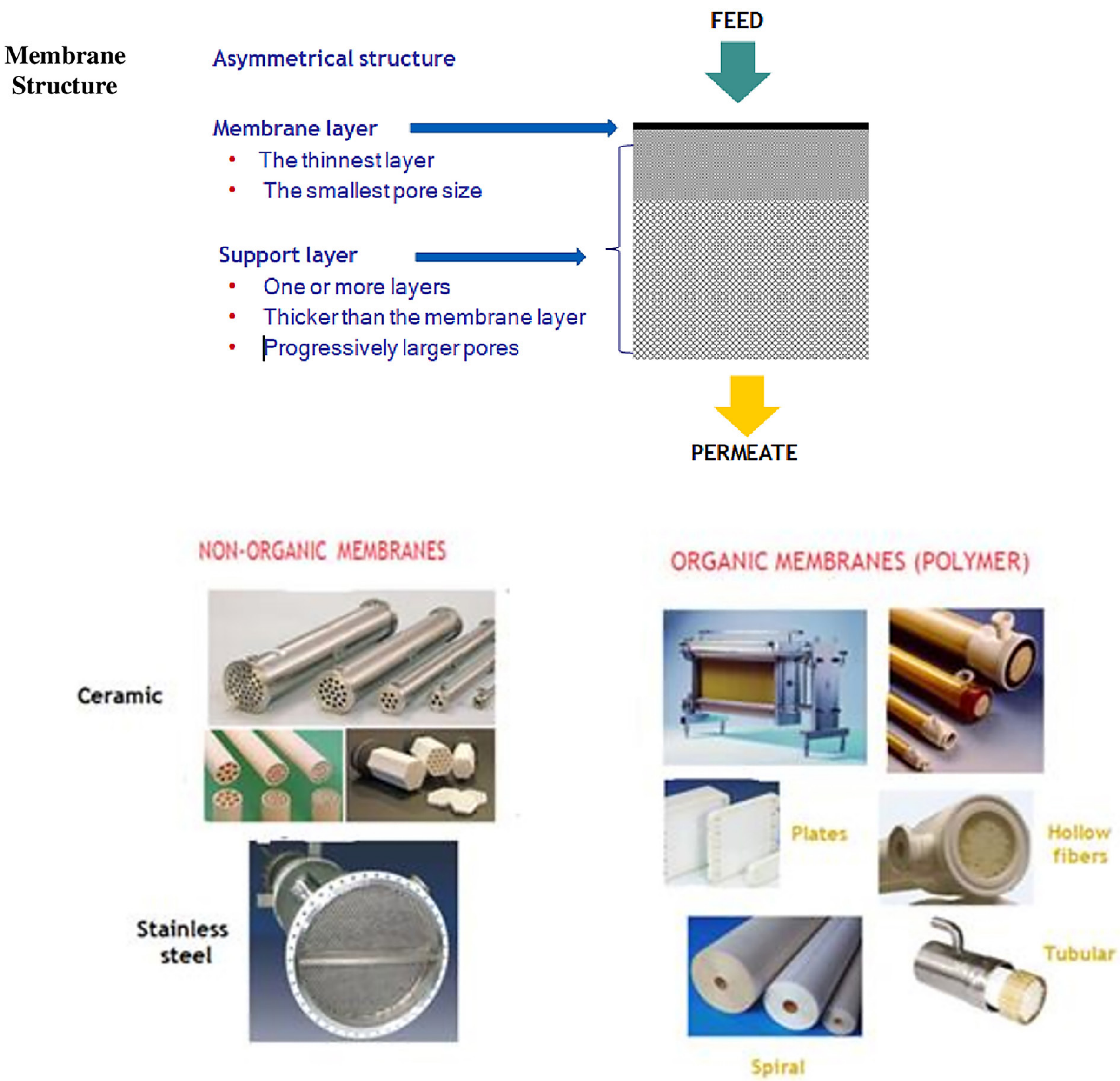

Figure 2. Overview of membrane structures and materials

In addition to the benefits offered by diafiltration alone, the integration of successive membrane filtration techniques such as: UF, NF, and RO Offers a sequential and precise separation of acid whey constituents. Kaur et al. (2020) highlighted that this combination facilitates the selective extraction of proteins during UF, minerals and sugars during NF, and concentrates residual solids with reverse osmosis, offering the possibility to create various products for a range of industries like food, cosmetics, and pharmaceuticals. Studies by Reig et al. (2021) and Kumar et al. (2013) reaffirm that these successive membrane operations facilitate circular economy strategies by recycling of permeate streams in processing, which lowers effluent volumes and reduces the environmental footprint.

Moreover, hybrid strategies that couple membrane filtration with complementary treatments have emerged as promising approaches to further enhance process efficiency and product quality. For instance, enzymatic hydrolysis prior to ultrafiltration, as demonstrated by Le et al. (2014), produces bioactive peptides by breaking down proteins, improving the selectivity of ultrafiltration and enriching the retentate with peptides that have significant functional and therapeutic potential. Similarly, Wen-qiong et al. (2019) showed that mild thermal treatments applied before or after membrane filtration maintain microbiological safety without degrading the functional properties of proteins, a critical factor for high quality dairy ingredients.

The current scientific literature robustly validates advanced membrane filtration configurations diafiltration, sequential membrane filtration, and hybrid processes as effective solutions to overcome existing challenges in acid whey valorization. These approaches not only optimize resource recovery and reduce waste but also enable the production of high-value functional ingredients. Consequently, they play a pivotal role in advancing sustainable and innovative practices within the dairy industry.

Fractionation of acid whey components

The evolution of membrane-based fractionation strategies for acid whey demonstrates the growing alignment between industrial innovation and scientific progress. While early applications of membrane technologies primarily focused on isolating whey proteins for use in nutritional supplements, modern approaches now adopt a broader perspective. These recent strategies aim to selectively recover and valorize each component of acid whey based on its specific composition and functional properties.

A significant example demonstrating this method can be found in the work of (Shekin, 2021; Lameloise, 2021) who developed a multi stage membrane sequence combining ultrafiltration (UF, 100 kDa), diafiltration (DF), and nanofiltration (NF, 200 Da). This integrated setup generated three characterized products were obtained: a retentate enriched in protein (8%) suitable for creating high protein drinks; a NF permeate containing a high concentration of lactose (12–14%), making it ideal for use in prebiotic synthesis or fermentation processes; and a concentrate rich in minerals that can be utilized in animal feed or as a source of electrolytes. This methodology illustrates an intentional pairing of each separated component with a targeted industrial use, thereby increasing the total value extracted from the original acid whey.

Expanding on this approach Almécija et al. (2007) utilized hydrophilic ceramic membranes operated under mild conditions (45–50 °C, 2 bar) to retain the integrity and biological efficacy of sensitive proteins, including α-lactalbumin.. The extracted protein fractions demonstrated improved antioxidant properties, making them suitable for integration in health-promoting foods, cosmetic products, or immune-boosting formulations. This study emphasizes the critical role of appropriate membrane choice combined with mild operational parameters in preserving the quality of bioactive substances.

Further advances were made by Chandrapala et al. (2017) who combined membrane filtration with pH adjustment (set to 6.2 before UF) to reduce the formation of protein-mineral complexes. This improved protein solubility and filtration performance, resulting in a 90% protein recovery rate and over 70% ash reduction, with only a 20% decline in membrane flux – a critical factor for industrial scalability. Their results emphasize the relevance of feed conditioning as a means of enhancing process efficiency.

To expand the range of valorized products, Wu et al. (2013) proposed a hybrid process that integrates UF with inline enzymatic hydrolysis. This technique allowed the partial breakdown of whey proteins during filtration, producing bioactive peptides with low molecular weight in the permeate. These peptides, known for their antihypertensive, antimicrobial, and immunomodulatory effects, represent a high-value output suitable for nutraceutical applications.

Pushing the boundaries of application, Darmali et al. (2022) introduced a multistep approach combining osmotic membrane separation (OI), nanofiltration, and vacuum evaporation. This method enabled the production of pharmaceutical-grade lactose (> 99.5% purity), suitable for applications such as tablet excipients and inhalation powders. This breakthrough positions acid whey as a promising feedstock for biorefinery-level processing.

Membrane-based fractionation of acid whey has transitioned into a highly specialized and application-driven platform. Innovations now focus not only on separating valuable components, but also on optimizing the performance and integration of the entire process. Future developments are likely to emphasize:

- Automation and real-time control of membrane operations;
- The use of advanced membranes (e.g., nanocomposites, graphene oxide, or responsive polymers);
- Full circular integration, including membrane regeneration and water reuse;
- Life-cycle analysis to assess the sustainability and cost-effectiveness of the processes.

These advances support a shift from waste treatment to resource valorization, establishing acid whey as a key raw material in sustainable and innovative bioprocessing systems.

Case studies, pilot applications, and industrial innovations

The valorization of acid whey through membrane technologies has become the subject of a growing number of pilot studies and industrial initiatives demonstrating its technical, economic, and environmental feasibility, while aligning with a transition towards circular economy models within the dairy industry. Since the 1980s, pioneering work by Smithers (2008) established that UF combined with diafiltration allowed obtaining high-purity serum protein concentrates, while simultaneously reducing lactose and mineral content, enabling targeted nutritional applications. This methodology was later refined, notably through the introduction of ceramic membranes, which are more resistant and less prone to fouling, as demonstrated by Saxena et al. (2009) and Baldasso et al. (2011) during pilot tests on acid whey clarification.

During the 2010s and 2020s, several industrial studies confirmed and expanded these approaches. For example, Arla Foods Ingredients developed integrated UF–NF processes combined with RO to treat acid whey from quark cheese, enabling efficient recovery of functional proteins (α-lactalbumin, immunoglobulins), production of concentrated lactose solutions, and reuse of treated water in industrial processes (Pires et al., 2021; Buchanan et al., 2023). In Iran implemented a pilot-scale UF-NF-RO chain valorizing Greek yogurt acid whey, producing protein concentrates for enrichment of fermented dairy products, crystallized lactose, and recycled water, illustrating a virtuous circular economy model (Farrukh, 2018; Bejarano-Toro et al., 2022). The European VALORLAC project (INRAE) proposed a major innovation combining membrane filtration (UF–RO) and enzymatic hydrolysis to generate bioactive peptides with antioxidant properties and angiotensin-converting enzyme (ACE) inhibitory activity, with confirmed stability in complex food matrices (Vargas et al., 2025). This process paves the way for the nutraceutical valorization of acid whey, an emerging field.In the United States, Dairy Management Inc conducted pilot trials integrating UF, diafiltration, NF, and RO with the objective of fractionating acid whey from Greek yogurt production into protein isolates, purified lactose destined for synthesis of galacto-oligosaccharides (GOS) with prebiotic effects, and recycled water (Ostertag et al., 2023). These isolates were successfully incorporated into infant formula prototypes, highlighting the functional and nutritional interest of the fractions obtained (Rocha-Mendoza et al., 2021). In Norway, the cooperative TINE SA developed an industrial prototype combining UF/NF membranes and membrane bioreactor (MBR) technology, achieving a 60% reduction in wastewater discharge while producing protein and lactose fractions for enriched beverages, with optimized water reuse (Talebi et al., 2020). This system represents a significant advancement in resource efficiency and sustainability.In Germany, Rektor et al. (2004) proposed a scheme integrating MF, UF, and NF to segment acid whey into fractions suitable for different sectors: infant nutrition, animal feed, and bioethanol production, demonstrating the multifunctional valorization potential of membrane technologies. In Spain, Ersahin et al.

(2012) developed targeted nanofiltration to recover minerals (calcium, phosphorus) and lactose, producing ingredients adapted to functional food applications and industrial commercialization. In Turkey, Sathya et al. (2023) tested spiral-wound NF membranes on acid whey from feta cheese, producing fractions rich in electrolytes and proteins for fermented beverages aimed at sports and medical markets. More recently, Charcosset (2021) explored an innovative membrane cascade system fractionating acid whey into four distinct streams (protein concentrate, lactose solution, mineral concentrate, purified water), highlighting the crucial importance of operating parameters (transmembrane pressure, flow velocity, temperature) and membrane material choice (PES vs. ceramic) to optimize yields.

Technological advances in 2023 have confirmed these trends, with studies reporting improvements in polymeric and ceramic membranes, energy optimization of processes, and integration of hybrid solutions combining membrane filtration, fermentation, and enzymatic hydrolysis. Zhang et al. (2023) developed composite membranes with high permeability and enhanced selectivity, suitable for valorizing protein and lactose fractions, while Kumar et al. (2013 and 2023) proposed an integrated approach combining ultrafiltration and enzymatic bioconversion for producing high-value bioactive peptides.

These advances demonstrate that membrane-based valorization of acid whey is now an industrially viable reality, contributing to a circular economy in the dairy industry by transforming by-products into functional and nutraceutical ingredients, as well as raw materials for innovative dairy product formulation, while minimizing environmental impact.

Future perspectives and challenges for an intelligent, sustainable and multifunctional valorization of acid whey

Future directions in the field of membrane fractionation of acid whey are driven by continuous innovation, guided by increasing demands for sustainability, technological performance, and diversification of applications. Firstly, a major priority lies in the automation and digitalization of membrane separation processes. The integration of smart sensors, real-time control systems such as SCADA (supervisory control and data acquisition) (Boyer, 2009), and predictive analytics based on artificial intelligence would allow continuous optimization of system performance (flow rates, selectivity, energy consumption), while reducing operational costs and product losses.Concretely, a SCADA system would enable centralized supervision of all filtration process steps through an interactive visual interface (Upadhyay and Sampalli, 2020). It records real-time critical data such as transmembrane pressure, permeate flow rate, pH, conductivity, and temperature, while issuing automatic alerts in case of deviations or malfunctions. These data can be cross-referenced with AI algorithms to anticipate membrane fouling, dynamically adjust operating parameters, or optimize cleaning-in-place (CIP) sequences based on real conditions, thus minimizing water, energy, and chemical usage. SCADA acts as an intelligent control tower, ensuring stability, traceability, and energy efficiency of the process. This automation will reinforce operational robustness at an industrial scale, especially in continuous or semi-continuous treatment units. Simultaneously, research is focusing on developing next-generation membranes that are more robust, selective, and durable. Efforts particularly focus on creating composite membranes combining functionalized polymers, nanostructured fillers (such as graphene, zeolites, or metal oxides), or modified active layers. These advanced membranes aim to reduce fouling, extend lifespan, and increase selectivity toward certain biomolecules like bioactive peptides or specific minerals. Additionally, biodegradable or recyclable membranes are being investigated from an eco-design perspective.Another promising approach lies in process intensification by combining membrane technologies with other transformation techniques such as enzymatic hydrolysis, targeted fermentation, or assisted extraction methods (ultrasound, high pressure, pulsed electric fields) (CUNHA et al., 2022). These synergies will multiply the valorization pathways of whey by producing, for example, high-value functional ingredients (hydrolyzed proteins, bioactive peptides, galacto-oligosaccharides, organic minerals) adapted to health nutrition, cosmetics, animal nutrition, or pharmaceutical sectors.

Towards innovative formulations incorporating acid whey fractions

A key perspective is the targeted integration of membrane-derived fractions into the formulation of new dairy and non-dairy products:

- **Protein-enriched fraction (UF retentates):** rich in functional and bioactive proteins, this fraction can be used to develop high-nutritional-value fresh cheeses, protein-enriched yogurts, or fermented beverages. It can also serve as a natural protein additive in sports nutrition or dietetic food formulations (Yorgun et al., 2008).
- **Concentrated whey fraction (NF/RO permeates):** through concentration and purification, these fractions rich in lactose and minerals can be valorized in desserts, ice creams, or as a natural sweet base in various beverages. Purified lactose is also an excellent substrate for prebiotic production (galacto-oligosaccharides) (Cuartas-Uribe et al., 2009).
- **Bioactive peptides and hydrolysates:** extracted via enzymatic hydrolysis of proteins, these components can be incorporated into nutraceuticals, cosmetics (anti-aging, moisturizing effects), or functional foods targeting cardiovascular or immune health.
- **Use in animal nutrition:** some fractions rich in peptides or organic minerals can enrich functional animal feeds, improving growth, digestive health, or immunity (Ayed et al., 2023).
- **Recycled process waters:** thanks to advanced treatments, waters from filtration can be reused in cleaning or production circuits, reducing the water footprint of dairies (Chamberland et al., 2020).

Thus, these approaches open the way to multifunctional product diversification, promoting healthier, innovative, and environmentally friendly formulations.

Challenges to overcome for optimized and sustainable valorization of acid whey

Despite numerous opportunities offered by membrane technologies and the integration of fractions into innovative formulations, several technical, economic, regulatory, and social challenges must be addressed to ensure fully efficient and sustainable valorization.

Membrane fouling and durability

Fouling is the main technical barrier to industrial membrane filtration. This complex phenomenon results from the accumulation of particles, colloids, biomolecules, and microorganisms on or inside membrane pores. Fouling causes progressive permeate flux decline, increased transmembrane pressure, and altered selectivity. To limit these effects, the development of advanced antifouling membranes incorporating hydrophilic materials, antimicrobial coatings, or functional nanomaterials is essential. Moreover, designing effective, water- and chemical-saving cleaning-in-place (CIP) protocols adapted to various foulants remains a major operational challenge. Optimizing these procedures is key to prolong membrane lifespan, reduce production downtime, and limit operational costs (Gésan-Guiziou et al., 2002).

Complexity and optimization of integrated processes

Integrating membrane technologies with complementary processes (enzymatic hydrolysis, fermentation, assisted extraction) requires fine and coordinated control of numerous operating parameters (temperature, pH, flow, residence time, enzyme concentration). This technical complexity demands the development of advanced modeling and control tools to ensure quality, reproducibility, and economic viability of produced fractions (Rosseto et al., 2024). Furthermore, managing flows and synchronizing steps must be optimized to avoid bottlenecks and minimize material losses.

Raw material variability

Acid whey is a complex and heterogeneous raw material whose composition varies according to multiple factors: milk type (cow, goat, sheep), animal diet and health, cheesemaking conditions (fermentation, rennet, drainage time), seasonality. This variability can affect membrane performance, fraction composition, and ultimately final product quality. Implementing real-time adaptation strategies through digitalization and predictive analytics is crucial to guarantee optimal standardization and limit quality deviations.

Investment and operational costs

Adopting advanced technologies such as composite membranes, SCADA systems, or coupled processes involves significant initial investment in equipment and personnel training. Operational costs related to energy, membrane maintenance, cleaning agents, and waste management must also be controlled. A rigorous techno-economic analysis including equipment lifecycle, return on investment, and potential financing (grants, public-private partnerships) is essential to ensure medium- and long-term profitability. Additionally, developing pilot and semi-industrial scale trials will facilitate assessment of real costs and potential gains (Shekin, 2021).

CONCLUSIONS

Acid whey, long underutilized in cheese production, can be effectively valorized through membrane filtration technologies. This study has enhanced the understanding of separation mechanisms and the impact of operational parameters on the quality of obtained fractions, notably the protein rich retentate (RUF), the lactose and mineral rich retentate (RNF), as well as the purified water permeate (ROS).

The results provide an integrated view of these processes, adapted to the specific needs of emerging dairy industries, especially in regions with strong cheese-making traditions. This work fills a significant gap by offering a combined analysis of mechanisms, technological performance, and practical industrial applications an approach rarely addressed before.

Furthermore, several avenues for improvement are identified: optimizing energy consumption, enhancing scalability of installations, and fully valorizing all co-products generated during filtration. The integration of diafiltration in processing chains also appears as a promising solution to increase fraction purity and functionality.

In summary, this research confirms that membrane filtration is a key technological pathway to transform a dairy waste into high-value resources, consistent with circular economy principles and sustainable development. Future prospects include the development of more efficient membranes, adaptation of processes to various industrial scales, and exploration of new applications for the recovered fractions, aimed at strengthening the competitiveness and sustainability of the dairy sector.

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