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Recent advances in membrane processing technologies for the dairy industry: Principles, applications, process innovations, challenges and future perspectives

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ABSTRACT

Membrane processing has become one of the most important separation, concentration and fractionation technologies in the modern dairy industry because it enables selective separation of milk constituents under comparatively mild processing conditions. Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF) and Reverse Osmosis (RO) are now widely applied for microbial reduction, milk protein standardization, fractionation of casein and serum proteins, whey protein concentration, partial demineralization, lactose-rich stream processing, milk and whey concentration and recovery of water and valuable constituents from dairy side streams. Unlike conventional thermal concentration, pressure-driven membrane processes can reduce thermal exposure and preserve the nutritional and functional characteristics of sensitive dairy components. Integration of membrane operations with diafiltration, evaporation, spray drying and other separation technologies has further expanded opportunities for manufacturing high-value milk and whey ingredients. Nevertheless, concentration polarization, protein and mineral fouling, flux decline, cleaning requirements, membrane deterioration, energy demand and process economics remain important limitations. Recent advances therefore emphasize multistage membrane processing, modified and charged membranes, improved hydrodynamic conditions, cold microfiltration, advanced fouling-control strategies and greater integration of membrane processes into resource-efficient dairy manufacturing. This review critically discusses the fundamental principles of membrane separation, major pressure-driven membrane technologies, dairy applications, protein fractionation, whey valorization, membrane fouling and cleaning, process integration, water recovery, sustainability, industrial challenges and future perspectives. Particular emphasis is placed on the transition from conventional concentration toward selective fractionation and integrated processing systems capable of producing high-value dairy ingredients while improving resource efficiency.

Keywords: Membrane processing, Dairy industry, Microfiltration, Ultrafiltration, Nanofiltration, Reverse osmosis, Milk proteins, Whey processing, Membrane fouling, Dairy sustainability

1. Introduction

The dairy industry processes a biologically and physicochemically complex raw material containing water, caseins, serum proteins, fat, lactose, minerals, vitamins and numerous minor bioactive constituents. Efficient separation and concentration of these components are fundamental to the production of conventional dairy products and increasingly important high-value ingredients such as milk protein concentrates, whey protein concentrates, whey protein isolates, micellar casein concentrates and specialized nutritional formulations. Conventional dairy separations have historically depended on centrifugation, precipitation, evaporation, thermal treatment and chemical processing. Although these operations remain essential, the increasing demand for minimally processed and compositionally defined dairy ingredients has encouraged adoption of technologies capable of providing greater molecular selectivity under comparatively mild conditions (Pouliot, 2008; Rosenberg, 1995) [1, 2].

Membrane processing has consequently become an integral component of modern dairy manufacturing. A membrane functions as a selective barrier that permits certain constituents of a feed stream to pass through while retaining others. Depending on membrane characteristics and operating conditions, separation may be influenced by particle size, molecular dimensions, charge, diffusivity and interactions between solutes and the membrane surface. The four major pressure-driven membrane processes used in dairy manufacture are microfiltration, ultrafiltration, nanofiltration and reverse osmosis. These technologies differ in pore characteristics, molecular-weight retention and operating pressure and therefore provide complementary separation capabilities (Pouliot, 2008; Shekin, 2021) [1, 3].

One of the principal advantages of membrane processing is the ability to separate or concentrate milk constituents without extensive phase change. Conventional evaporation requires considerable thermal energy for

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water vaporization, whereas pressure-driven membrane concentration removes water through a selective barrier. Consequently, membrane processing can reduce thermal exposure and may better preserve the functional properties of heat-sensitive dairy constituents. This advantage is particularly relevant to serum proteins, which can undergo denaturation and aggregation following extensive thermal treatment (Rosenberg, 1995; Tomasula *et al.*, 2015) [2, 4].

Microfiltration is particularly important for microbial reduction and separation of casein micelles from serum proteins, whereas ultrafiltration is extensively employed to retain and concentrate proteins while allowing water, lactose and many soluble minerals to enter the permeate. Nanofiltration provides an intermediate separation between UF and RO and is useful for simultaneous concentration and partial demineralization. Reverse osmosis retains most milk solids and primarily removes water, making it valuable for pre-concentration before evaporation and drying (Shekin, 2021; Tomasula *et al.*, 2015) [3, 4].

The importance of membrane technology has increased further with the transformation of whey from an environmental burden into a source of valuable food ingredients. Membrane processes allow whey proteins to be concentrated and purified while lactose- and mineral-rich permeates can undergo additional processing. Similar technologies can be used for milk protein fractionation, dairy-product standardization and recovery of water and useful components from dairy side streams (Marella *et al.*, 2013; Pouliot, 2008) [5, 1].

Despite these advantages, membrane processing remains constrained by concentration polarization and membrane fouling. Proteins, lipids, minerals, microorganisms and other constituents can accumulate at or within membrane surfaces, increasing hydraulic resistance and reducing permeate flux. Fouling may also modify membrane selectivity, increase energy requirements and necessitate frequent cleaning. Consequently, the future development of dairy membrane processing depends not only on improved selectivity but also on maintaining stable performance during prolonged industrial operation.

The present review critically examines the principles and recent advances in membrane processing technologies relevant to the dairy industry, with particular emphasis on MF, UF, NF, RO, diafiltration, protein fractionation, whey valorization, microbial reduction, fouling and cleaning, process integration, sustainability and future industrial perspectives.

2. Fundamental principles of membrane processing

Membrane separation involves transport of selected constituents across a semipermeable barrier under an applied driving force. In pressure-driven dairy membrane processes, transmembrane pressure represents the principal driving force. The original feed is separated into two streams: the retentate, containing components preferentially retained by the membrane and the permeate, containing water and constituents capable of passing through the membrane (Pouliot, 2008; Tamime, 2013) [1, 6].

The separation characteristics of a membrane depend on pore dimensions, molecular-weight cut-off, membrane composition, surface charge and hydrophobicity as well as the physicochemical characteristics of the feed. MF membranes have relatively large pores and can retain bacteria, fat globules, casein micelles and suspended particles depending on pore size. UF membranes retain proteins and other macromolecules while allowing lactose, water and many soluble minerals to pass. NF provides greater retention of small organic molecules and multivalent ions, whereas RO uses comparatively dense membranes and principally permits water transport (Shekin, 2021) [3]. Dairy membrane operations are predominantly conducted in cross-flow rather than dead-end configuration. During dead-end filtration, the feed moves toward the membrane surface and retained material rapidly accumulates. In cross-flow filtration, the feed moves tangentially across the membrane while permeate passes through it. Tangential flow produces shear at the membrane surface and reduces, although does not eliminate, deposition of retained constituents (Tamime, 2013) [6].

Permeate flux is an important indicator of membrane productivity. It is influenced by transmembrane pressure, feed viscosity, temperature, cross-flow velocity, membrane resistance, concentration polarization and fouling. Increasing pressure can initially increase permeate flux, but beyond a particular range the effect becomes progressively smaller because accumulation of retained material produces additional resistance. Excessive pressure can also compact deposited layers, potentially worsening flux decline.

Temperature has similarly complex effects. Increasing temperature generally reduces feed viscosity and can increase permeate flux; however, elevated temperatures may also alter protein interactions, microbial growth and mineral equilibria. Cold membrane processing has therefore received increasing attention for selected dairy applications, particularly microfiltration of milk, where lower temperatures may reduce microbial growth during extended filtration operations (Wang *et al.*, 2019) [7].

3. Major membrane technologies in dairy processing

3.1 Microfiltration

Microfiltration is the most open of the four major pressure-driven membrane processes used in dairy processing. Depending on pore size and operating conditions, MF can permit passage of water, lactose, minerals and serum proteins while retaining bacteria, fat globules and casein micelles. This characteristic makes MF particularly valuable for microbial reduction and milk-protein fractionation (Elwell *et al.*, 2006; Tomasula *et al.*, 2015) [8, 4].

One of the best-established dairy applications is the removal of microorganisms from skim milk. Elwell *et al.* (2006) [8] demonstrated substantial reductions in bacterial counts through microfiltration and showed that combining MF with pasteurization can markedly improve microbial quality. Because the separation is physical rather than based entirely on heat inactivation, MF provides an opportunity to reduce microbial load while limiting severe heat-induced changes.

Cold microfiltration has subsequently attracted attention as an alternative to conventional warm MF. Wang *et al.* (2019) [7] investigated skim milk processed by cold MF using a 1.4- μm membrane and evaluated its microbial and proteolytic shelf-life characteristics. Cold operation may reduce the risk of thermophilic bacterial growth and biofilm formation during processing, although reduced temperature increases viscosity and can influence flux.

Another major application of MF is the fractionation of casein micelles from serum proteins. Casein micelles are substantially larger than individual whey proteins, allowing appropriately selected MF membranes to retain casein while permitting a proportion of serum proteins to pass into the permeate. This has enabled production of micellar casein concentrates and milk-derived whey protein ingredients with distinctive compositional and functional properties (Marella *et al.*, 2013; Tomasula *et al.*, 2015) [5, 4].

The efficiency of casein-serum protein separation is influenced by membrane pore size, temperature, transmembrane pressure, cross-flow velocity, concentration factor and diafiltration conditions. Consequently, MF should be considered a dynamic separation process in which hydrodynamics and deposit-layer formation can influence apparent selectivity.

3.2 Ultrafiltration

Ultrafiltration is one of the most extensively applied membrane operations in dairy processing. UF membranes generally retain proteins, fat and macromolecular material while allowing water, lactose and a substantial proportion of soluble minerals to pass through the membrane. This selectivity has made UF fundamental to the production of protein-enriched dairy ingredients (Arunkumar *et al.*, 2018; Gavazzi-April *et al.*, 2018) [9, 10].

Milk protein concentrates are commonly manufactured by ultrafiltration of skim milk. As filtration progresses, caseins and serum proteins become concentrated in the retentate while lactose and soluble minerals preferentially enter the permeate. Diafiltration can subsequently be

used to increase the protein-to-total-solids ratio by adding water to the retentate while continuing filtration (Gavazzi-April *et al.*, 2018) [10]. Membrane properties can be deliberately modified to improve UF performance. Arunkumar *et al.* (2018) [9] demonstrated the use of negatively charged, wide-pore UF membranes for milk protein concentration. Electrostatic repulsion contributed to protein retention, illustrating that modern membrane selectivity can be engineered through surface properties rather than relying solely on size exclusion.

Ultrafiltration also has important applications in cheese manufacture. Concentrating milk proteins before coagulation can increase cheese-milk solids, reduce whey volume and modify processing efficiency. The effect on the final product depends on the concentration level and the retention of lactose and minerals, which influence acidification, curd formation and cheese composition (Lauzin *et al.*, 2020).

UF has also been investigated for yoghurt manufacture. Valencia *et al.* (2018) [11] demonstrated that ultrafiltration of milk before fermentation can influence mass balance and process efficiency in Greek-style yoghurt manufacture. Such applications demonstrate that membrane technology can contribute not only to ingredient production but also to restructuring conventional dairy-manufacturing processes.

3.3 Nanofiltration

Nanofiltration occupies an intermediate position between ultrafiltration and reverse osmosis. NF membranes generally retain lactose and many multivalent ions while allowing greater passage of water and some monovalent ions. This characteristic enables simultaneous concentration and partial demineralization of selected dairy streams (Pouliot, 2008; Shekin, 2021) [1, 3].

Whey and UF permeates are important candidates for nanofiltration because these streams contain substantial concentrations of lactose and minerals. NF can concentrate lactose-containing solids while allowing partial mineral removal, thereby reducing the water load entering subsequent evaporation and drying operations.

The performance of NF depends strongly on membrane charge, feed pH, ionic composition, pressure and concentration. Unlike simple particle sieving, separation of ions is influenced by electrostatic interactions and coupled transport. Consequently, mineral rejection can change as the feed becomes progressively concentrated.

NF also has potential in integrated dairy-water recovery systems. When applied after suitable pretreatment, it can reduce dissolved organic matter and selected ions before further purification. Its role is therefore expanding from product concentration toward broader resource-recovery applications.

3.4 Reverse osmosis

Reverse osmosis employs dense membranes and comparatively high operating pressures. Most dissolved and dispersed dairy constituents are retained, whereas water preferentially passes through the membrane. RO is therefore primarily a concentration rather than fractionation technology (Pouliot, 2008) [1].

Pre-concentration of milk or whey by RO can reduce the amount of water that subsequently needs to be removed by evaporation. Because pressure-driven water removal does not require vaporization, integrating RO before thermal concentration can reduce energy requirements and thermal exposure.

The properties of RO concentrates are not necessarily identical to those of UF concentrates because RO retains lactose and minerals along with proteins. Lauzin *et al.* (2020) [12] demonstrated differences in cheese making behavior between milk concentrated by RO and UF, illustrating that selection of the membrane process can influence the physicochemical characteristics of the resulting dairy product.

RO also has potential for recovering water from selected dairy streams. However, the suitability of RO permeate for reuse depends on the composition of the feed, membrane integrity, microbiological quality and the intended reuse application.

4. Diafiltration and multistage membrane processing

Diafiltration is commonly combined with UF or MF when greater removal of permeable solutes is required. Water is added to the retentate while filtration continues, allowing lactose, minerals and other permeable constituents to move into the permeate while retained proteins remain concentrated. Diafiltration is therefore central to the manufacture of high-protein milk ingredients and highly purified casein-rich fractions (Gavazzi-April *et al.*, 2018) [10].

The design of diafiltration strongly affects process efficiency. Continuous diafiltration can reduce water requirements and improve process control compared with less optimized approaches. Gavazzi-April *et al.* (2018) [10] demonstrated that process design affects the overall efficiency of milk protein concentrate production, emphasizing the importance of considering mass balance and water use in addition to final composition.

Commercial dairy membrane plants frequently operate as multistage systems. Blais *et al.* (2022) [13] emphasized that industrial installations use sequential membrane stages to improve flux performance, membrane selectivity and processing efficiency. Retentate or permeate from one stage may become the feed for another, allowing complementary membrane characteristics and operating conditions to be exploited.

The transition from laboratory single-stage studies to industrial multistage processing is particularly important when interpreting membrane research. Performance observed in a small batch unit cannot automatically be extrapolated to a commercial plant, where concentration gradients, residence times, pressure distribution and fouling conditions may differ substantially (Blais *et al.*, 2022) [13].

5. Milk protein fractionation and development of high-value ingredients

The increasing demand for specialized milk-protein ingredients is one of the principal drivers of membrane innovation. Milk contains caseins organized predominantly as colloidal micelles and smaller serum proteins dispersed within the aqueous phase. Their difference in dimensions provides the basis for controlled fractionation by MF (Marella *et al.*, 2013) [5].

Micellar casein concentrate can be produced by MF of skim milk followed by diafiltration. The casein-rich retentate can subsequently be concentrated and dried, whereas the permeate contains serum proteins together with lactose and minerals. Because this process does not require acid or enzymatic precipitation of casein, the resulting ingredient can retain casein in a state closer to its native micellar organization.

Milk-derived whey proteins obtained through MF differ from conventional cheese whey proteins because they are recovered directly from milk without exposure to cheesemaking conditions. This has created considerable interest in native serum-protein ingredients for specialized food and nutritional applications.

UF can subsequently concentrate the serum-protein fraction. The combination of MF and UF therefore provides a platform for sequential fractionation of milk into casein-rich and whey-protein-rich streams. Membrane technology can similarly be used to standardize protein concentrations before manufacture of cheese and fermented dairy products, improving processing consistency despite seasonal changes in raw milk composition (Pouliot, 2008) [1].

Membrane charge represents another opportunity for improved protein selectivity. Arunkumar *et al.* (2018) [9] demonstrated that negatively charged UF membranes can retain negatively charged milk proteins through electrostatic repulsion while using larger pores that permit improved permeate flux. This illustrates the transition from conventional pore-size-based separation toward engineered membrane-protein interactions.

6. Whey processing and valorization

Whey valorization represents one of the most commercially successful applications of dairy membrane technology. Cheese whey contains valuable proteins, lactose and minerals but also has a high organic load. Its conversion into food ingredients therefore provides both economic and environmental advantages (Marella *et al.*, 2013; Rosenberg, 1995) [5, 2].

Ultrafiltration is the principal membrane technology used for whey protein concentration. Whey proteins are retained while a substantial proportion of lactose, water and soluble minerals enters the permeate. The resulting retentate can be further concentrated and dried to produce whey protein concentrates.

Diafiltration can increase protein purity by washing lactose and minerals from the protein-rich retentate. More highly purified protein ingredients can subsequently be produced through combinations of UF, diafiltration and additional separation technologies.

The permeate remaining after whey protein concentration should itself be regarded as a resource rather than a waste stream. It contains lactose, minerals and water and can be processed using NF, RO and other technologies. This sequential approach improves utilization of the original whey stream and supports circular dairy-processing strategies.

Membrane fractionation has therefore contributed substantially to the transformation of whey from a disposal problem into a raw material for protein, carbohydrate and mineral ingredients. Future whey processing is likely to involve even greater fractionation into compositionally defined streams rather than production of a limited number of bulk ingredients.

7. Membrane fouling and concentration polarization

Membrane fouling remains one of the most important technological constraints in dairy membrane processing. Milk and whey contain proteins, fat, minerals, microorganisms and other constituents capable of interacting with membrane surfaces and pores. Accumulation of these components increases resistance to permeate flow and causes progressive flux decline.

Concentration polarization occurs when retained solutes accumulate near the membrane surface faster than they can be transported back into the bulk feed. The resulting concentration boundary layer reduces the effective driving force and can facilitate gel-layer formation and more persistent fouling. Concentration polarization is generally considered more reversible than strongly adsorbed or pore-blocking fouling, but the two phenomena are closely connected during practical dairy processing.

Protein fouling is particularly important. Casein micelles can form deposited layers during MF and UF, whereas serum proteins may adsorb onto membrane materials. Mineral constituents, particularly calcium and phosphate species, can contribute to inorganic deposits and can interact with proteins to form complex foulant structures.

Operating conditions strongly influence the development of fouling. Increasing cross-flow velocity generally improves mass transfer and reduces accumulation at the membrane surface, although this increases pumping requirements. Increasing transmembrane pressure may initially improve flux but can eventually compress the fouling layer. Temperature influences viscosity, protein interactions and mineral equilibria and therefore has both direct and indirect effects on fouling.

Fouling also influences selectivity. A deposited protein layer can effectively behave as a secondary membrane, modifying the passage of serum proteins, minerals and other components. Consequently, membrane performance should not be characterized only by the properties of the clean membrane.

8. Cleaning and fouling-control strategies

Cleaning-in-place is essential for restoring membrane performance and maintaining hygienic dairy processing. A typical cleaning sequence may include water rinsing, alkaline cleaning, acid cleaning

and appropriate sanitization. Alkaline solutions are effective against proteinaceous and lipid soils, whereas acidic solutions assist in removing mineral deposits.

Cleaning performance depends on chemical concentration, temperature, contact time, flow velocity and membrane compatibility. Increasing chemical concentration or temperature can improve soil removal but may accelerate membrane deterioration. Cleaning therefore requires optimization rather than simply applying the most severe conditions possible.

The environmental consequences of cleaning are increasingly important because frequent cleaning consumes water, energy and chemicals and generates wastewater containing organic matter, salts and cleaning agents. Reducing fouling formation can therefore provide both economic and environmental benefits.

Future fouling-control strategies are expected to combine optimized hydrodynamics, improved feed pretreatment, modified membrane surfaces and process monitoring. Surface modification that increases hydrophilicity or modifies charge can potentially reduce protein adsorption. The charged-membrane approach investigated by Arunkumar *et al.* (2018) [9] demonstrates how membrane surface properties can simultaneously influence protein retention and filtration performance.

9. Applications in dairy product manufacture

Membrane technology is increasingly integrated directly into dairy-product manufacture rather than being restricted to ingredient processing. UF can standardize protein concentrations in cheese milk and reduce the volume of material processed during subsequent stages. However, retention or removal of lactose and minerals influences acidification and curd properties, making process selection important for final product quality.

Lauzin *et al.* (2020) [12] compared milk concentrates produced using RO and UF and demonstrated that the different retention characteristics of these technologies influence cheese making properties. RO retains lactose and minerals with the proteins, whereas UF selectively removes many smaller solutes. Therefore, equal total-solids concentration does not imply equivalent functionality.

In fermented dairy manufacture, UF can increase protein concentration before fermentation. Valencia *et al.* (2018) [11] investigated UF as an alternative processing route for Greek-style yoghurt and demonstrated its implications for mass balance and processing efficiency. Membrane concentration before fermentation can reduce or eliminate the need for post-fermentation whey separation, thereby influencing both yield and side-stream generation.

Membrane processing can also be used in fluid-milk manufacture. Microfiltration can reduce bacterial and spore counts and, when combined with appropriate heat treatment and refrigerated storage, can contribute to extended shelf life (Elwell *et al.*, 2006; Wang *et al.*, 2019) [8, 7].

These applications demonstrate that membrane processing is not simply an ingredient-separation technology. It can fundamentally alter the sequence and mass balance of conventional dairy manufacturing.

10. Process integration and recent innovations

The greatest industrial value of membrane technology frequently arises from integration of multiple separation operations. MF can initially fractionate casein from serum proteins, UF can concentrate the resulting protein streams, NF can concentrate and partially demineralize lactose-rich permeates and RO can remove additional water. Such integration allows different membrane selectivities to be used sequentially (Blais *et al.*, 2022) [13].

Membrane concentration can also be integrated with evaporation and spray drying. Removing a portion of water using RO before evaporation reduces the quantity that must subsequently be vaporized. UF or MF can simultaneously modify composition before thermal concentration. Hybrid processing therefore combines the selectivity of membranes with the high final concentration achievable by evaporation.

Multistage operation is particularly important at industrial scale. Blais *et al.* (2022) [13] emphasized that commercial dairy plants commonly use multistage sequential filtration to improve efficiency when processing complex streams such as milk and whey. Future research should therefore increasingly reproduce industrial flow arrangements rather than relying exclusively on single-stage laboratory experiments.

Modified membrane surfaces represent another area of innovation. Charged membranes demonstrate that electrostatic interactions can be exploited to increase protein retention while using comparatively large pores (Arunkumar *et al.*, 2018) [9]. Future membrane design may increasingly combine pore-size control with tailored surface chemistry.

Process monitoring and digital control are also likely to become increasingly important. Pressure, temperature, conductivity, turbidity, flow and permeate-flux measurements can provide information regarding changing process conditions. Data-driven models could eventually predict the onset of severe fouling and assist in determining optimum cleaning intervals.

11. Dairy wastewater treatment and water recovery

Dairy manufacturing generates wastewater containing organic material, nutrients, suspended solids, cleaning chemicals and salts. Membrane processes can be integrated into treatment systems to recover water and potentially valuable constituents while reducing pollutant discharge.

UF can remove suspended and macromolecular material, whereas NF and RO provide progressively greater removal of dissolved components. The appropriate sequence depends on wastewater composition and the quality required for the recovered water.

Water recovery is particularly relevant because dairy processing consumes substantial quantities of freshwater for processing, cleaning and utilities. Water originally present in milk and whey also represents a potentially recoverable resource during concentration operations.

However, water reuse in food manufacture requires careful microbiological and chemical assessment. The fact that water has passed through a membrane does not automatically make it suitable for direct food contact. Membrane integrity, pretreatment, post-treatment and intended reuse must all be considered.

Future dairy facilities may increasingly integrate product recovery and water treatment. In such systems, streams traditionally classified as waste may be sequentially processed to recover proteins, lactose, minerals and water before final discharge.

12. Sustainability and energy efficiency

Membrane processing can contribute to sustainable dairy manufacturing by reducing thermal concentration requirements, increasing recovery of valuable components and facilitating water reuse. Whey valorization is one of the clearest examples because membrane fractionation converts a high-organic-load side stream into valuable protein ingredients and additional streams suitable for lactose and mineral recovery.

UF has also demonstrated opportunities to improve the resource efficiency of specific dairy products. Valencia *et al.* (2018) [11] evaluated mass balance and process efficiency when UF was applied before Greek-style yoghurt fermentation, illustrating how membrane processing can influence not only product composition but also material utilization.

However, membrane technology should not automatically be considered environmentally superior. Pumps consume electrical energy, membranes require manufacturing and periodic replacement and cleaning consumes chemicals, water and heat. Concentrated cleaning effluents must also be treated.

Multistage systems can potentially improve sustainability by optimizing flux and separation performance, but their benefits should be quantified through comprehensive mass and energy balances. Blais *et*

al. (2022) [13] emphasized the importance of multistage configurations in improving processing efficiency at industrial scale.

Future comparisons should therefore include life-cycle assessment and techno-economic analysis alongside conventional membrane parameters. A process that achieves slightly greater selectivity but requires substantially greater energy or cleaning intensity may not provide the best overall industrial solution.

13. Challenges and limitations

Despite extensive industrial application, several limitations continue to restrict membrane performance. Fouling and flux decline remain dominant concerns because they reduce productivity, modify selectivity and increase cleaning frequency. Feed composition also varies naturally, meaning membrane systems must operate effectively despite seasonal and processing-related variation.

Achieving high concentration factors presents another challenge. As solids concentration increases, viscosity rises and mass transfer becomes increasingly difficult. Osmotic pressure becomes especially important in NF and RO, while concentration polarization becomes increasingly severe in protein-rich UF and MF retentates.

Membrane lifetime is an important economic consideration. Membranes must tolerate prolonged contact with milk constituents as well as repeated cycles of alkaline, acidic and sanitizing chemicals. Novel membrane materials that demonstrate excellent short-term selectivity may have limited commercial relevance if their performance deteriorates rapidly under industrial cleaning conditions.

The translation of laboratory research to commercial production also remains problematic. Laboratory membrane systems often use small feed volumes, simplified flow paths and short operating periods. Industrial installations process large quantities continuously or semi-continuously and commonly use multistage arrangements. Consequently, long-duration trials and realistic cleaning cycles should become a greater component of membrane research (Blais *et al.*, 2022) [13].

14. Future perspectives

Future dairy membrane processing is expected to shift increasingly from bulk concentration toward precision fractionation. Growing demand for native proteins, high-purity casein fractions, serum proteins and specialized nutritional ingredients will encourage development of membranes capable of discriminating among components with increasingly similar physicochemical characteristics.

Surface engineering is likely to contribute to this development. Charged and hydrophilic membranes may provide greater control over protein-membrane interactions and reduce fouling. The performance improvements demonstrated with negatively charged UF membranes indicate the potential of combining pore architecture with electrostatic selectivity (Arunkumar *et al.*, 2018) [9].

Cold membrane processing is another promising direction. Cold MF can potentially reduce microbial growth and biofilm formation during extended processing while preserving native protein structures. However, lower temperature increases viscosity and can reduce permeate flux, requiring optimization of hydrodynamics and membrane area (Wang *et al.*, 2019) [7].

Multistage processing is likely to become increasingly sophisticated. Rather than considering MF, UF, NF and RO as independent technologies, future dairy plants may use them as interconnected fractionation platforms. The permeate and retentate generated at each stage can be directed toward additional processing according to composition and product value (Blais *et al.*, 2022) [13].

Digital monitoring and predictive process control represent another important opportunity. Real-time data on pressure, flux, conductivity, temperature and composition could be combined with predictive models to identify fouling development, optimize cleaning schedules and improve product consistency.

Sustainability will remain a major driver of innovation. Future membrane systems should maximize recovery of proteins, lactose, minerals and water while reducing cleaning intensity and energy consump

tion. This will require closer integration between product processing and wastewater management.

Importantly, future membrane research should evaluate new technologies according to industrially meaningful criteria. Initial clean-water flux or short-duration protein rejection alone is insufficient. Membrane lifetime, fouling behavior, cleanability, energy requirement, process yield, product functionality and economic feasibility should be evaluated over repeated production and cleaning cycles.

Conclusion

Membrane processing has become an important technology in the dairy industry for microbial reduction, protein fractionation, concentration, demineralization and water removal. Microfiltration, ultrafiltration, nanofiltration and reverse osmosis enable efficient production of high-value milk and whey ingredients while reducing extensive thermal processing (Pouliot, 2008; Tomasula *et al.*, 2015) [1, 4]. Recent developments, including charged membranes, cold microfiltration and multistage membrane systems, have further improved separation efficiency and process flexibility (Arunkumar *et al.*, 2018; Blais *et al.*, 2022; Wang *et al.*, 2019) [9, 13, 7]. However, membrane fouling, flux decline, cleaning requirements, membrane durability and processing costs remain major challenges. Future developments should therefore focus on fouling-resistant membranes, improved process integration, resource recovery and energy-efficient operation. Overall, the integration of advanced membrane engineering with sustainable dairy processing offers considerable potential for producing high-quality dairy ingredients while improving water, energy and raw-material utilization.

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