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Use of Membrane Technologies to Increase Protein Content in Dairy Products

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Abstract

The article considers modern approaches to increasing protein content in dairy products using membrane technologies. The introduction substantiates the relevance of the topic, including in the context of the growing demand for functional and high-protein products. A literature review is conducted, the scientific gap is identified and the objectives and hypotheses of the study are formulated. Further, the first section presents the basics of membrane filtration and membrane materials, and a comparative analysis of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) processes is made. Key factors affecting membrane performance (foliation, concentration polarization, etc.) and optimization methods (feedstock pretreatment, pressure and temperature control, CIP cleaning methods) are discussed. The second section describes in detail technological schemes with integration of different types of membranes in raw milk and whey processing, which allows to enrich finished products with protein and simultaneously reduce production losses. Special attention is paid to the increase of cheese yield due to the concentration of casein micelles, as well as to the production of valuable whey proteins (WPC, WPI) and reduction of lactose content. The obtained results and systematization of data indicate high efficiency of membrane technologies in dairy production, allowing to produce products with a given level of protein, improve quality and provide resource saving.

Keywords: dairy industry; membrane technology; microfiltration (MF); ultrafiltration (UF); nanofiltration (NF); reverse osmosis (RO); protein enhancement; whey proteins; lactose; diafiltration.

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1. Introduction

The modern dairy industry is undergoing substantial qualitative changes driven by a growing demand for functional and high-protein products, such as protein-fortified beverages, yogurts with elevated protein content, as well as infant formulas and sports nutrition [1, 2]. According to the Food and Agriculture Organization of the United Nations in 2021, milk production and dairy processing are steadily increasing, particularly in countries with well-developed agricultural sectors. Consequently, there is a rising need for technologies capable of producing more concentrated protein fractions while preserving their functional properties (solubility, emulsification, and foaming). Traditional methods, including evaporation or the use of chemical coagulating agents, often face product-quality constraints and pose questions about energy efficiency.

Membrane processes, originally employed primarily for the clarification and dehydration of feedstock in the food industry, have become increasingly important in recent decades as key tools for fractionating, concentrating, and enhancing protein constituents [3]. Combining microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) enables the effective separation and concentration of whey proteins, casein micelles, and the removal of excessive lactose and salts [4]. Thus, the relevance of this topic is driven both by market demand for protein-rich products and by the need for resource-efficient and environmentally safe technologies in dairy enterprises.

Various researchers have explored the potential of membrane methods for processing milk, whey, and related by-product streams in the food industry. In the study by Reig, Vecino, and Cortina [3], microfiltration (MF) was shown to be widely applied for microbial reduction and defatting, while ultrafiltration (UF) is particularly useful for the concentration of whey proteins (WPC) and the production of their isolates (WPI). According to Daufin and his colleagues [2], one of the most significant recent advances has been the implementation of nanofiltration (NF) and reverse osmosis (RO) for partial demineralization of dairy streams and the concentration of ultrafiltration permeates, helping manufacturers create new products with high protein content but minimal lactose and mineral salts.

A number of reviews [1, 4] have emphasized that membrane processes operate at relatively low temperatures, which helps protect thermolabile proteins. They also note the advantages of integrated schemes (e.g., MF + UF + NF) in which each stage is optimized for a particular fraction—from large fat/casein particles to smaller whey proteins [5]. However, despite the active adoption of membrane systems, critical challenges remain: membrane fouling, the need for complex cleaning-in-place (CIP) procedures, and the relatively high cost of certain membrane types [3].

Most studies focus on specific individual stages, such as the concentration of whey protein, lactose reduction, or increasing cheese yield by membrane pretreatment of raw milk. Yet a growing priority is a more holistic approach that would deploy membrane technologies across multiple steps of milk and whey processing to (1) enhance the protein value of the final product, (2) reduce energy consumption, and (3) minimize waste. The literature still lacks adequate discussion on systemic integration and the design of multi-stage industrial membrane schemes that simultaneously address protein enrichment and environmental safety.

Hence, the goal of this work is to justify a multi-stage membrane arrangement—encompassing micro-, ultra-, nano-, and reverse-osmosis filtration—at various stages of dairy processing, focusing on increasing protein content in the end product and reducing production losses.

The proposed research contributes to the field of food and membrane technologies by:

1. Compiling current data on different membrane types (ceramic and polymeric) and operating conditions relevant to the dairy industry;
2. Presenting a comprehensive technological framework that maximizes the advantages of protein fractionation and concentration, while reducing lactose and mineral content;
3. Evaluating the effects of membrane fouling and preventive measures in real-world industrial settings (including both economic and ecological dimensions).

Our hypothesis holds that an integrated membrane technology (combining MF, UF, NF, and RO in a single production cycle) can achieve higher yields and better preservation of proteins (including whey proteins) compared to conventional concentration and separation methods. At the same time, such a system should improve energy efficiency and reduce wastewater volumes through the selective removal of lactose and mineral salts.

2. Principles and classification of membrane processes in the dairy industry

Membrane filtration in the food sector is based on the selective passage of dissolved or suspended components through a semipermeable membrane under differences in pressure, concentration, and/or electrical potential. In dairy applications, pressure is usually the main driving force for separation (*pressure-driven membrane processes*) [1, 3, 8]. The core separation mechanism can depend on particle size—where larger molecules such as bacteria, casein micelles, or large fat globules are retained while smaller components like lactose and low-molecular-weight salts pass into the permeate—on molecular weight cut-off (MWCO), which defines how certain proteins are excluded, on electrical charge (especially relevant to nanofiltration (NF) and reverse osmosis (RO) in achieving ion-selective removal), and on hydrodynamic pressure coupled with concentration polarization, where elevated pressures can increase permeation but also raise the risk of fouling [8, 9].

Membranes used for milk and whey processing are commonly made from different materials. Polymeric membranes are often composed of polyethersulfone (PES), polyamide (PA), polyvinylidene fluoride (PVDF), and occasionally polysulfone (PS). They generally offer a cost-effective ratio of performance to price, good productivity, and relatively simple construction for spiral-wound modules [1, 9]. At the same time, they have a limited pH range (usually 2–11), and operating temperatures usually do not exceed about 50–60 °C. They can also be vulnerable to aggressive cleaning chemicals or high-temperature sanitization procedures [3, 8]. Ceramic membranes commonly rely on aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), or silicon carbide (SiC). They exhibit high chemical resistance (pH 0–14), can operate at temperatures ranging from 80 °C to 150 °C, and can undergo intense cleaning (NaOH, HNO_3), thereby extending their lifespan [6]. However, they cost more to produce and often have a lower packing density (m^2/m^3) than polymeric equivalents [6].

The choice of membrane material depends on the properties of the feed (skim milk or whey, acidity, microbial load) and on desired final product characteristics, such as the degree of demineralization or protein concentration [10].

Typical designs and configurations of membrane modules include:

- **Spiral-wound**: widely used in ultrafiltration (UF) and nanofiltration (NF) for dairy applications, owing to high membrane area per volume and relatively easy operation [4].
- **Tubular**: these consist of cylindrical channels with permeable walls and are well-suited for microfiltration and ultrafiltration of high-viscosity liquids like whey concentrates.
- **Ceramic multichannel**: a monolithic tube with multiple parallel channels that increase the filtration surface area. This design is especially popular for microfiltration (MF) and UF processes under harsh conditions (high temperature, extreme pH) [3, 6, 10].

Membrane technologies also vary by pore size (or molecular weight cut-off) and operating pressure. Table 1 summarizes the key characteristics of the main processes (MF, UF, NF, RO) for increasing protein content in dairy products.

Table 1: Comparative overview of key membrane processes in the dairy industry

Process	**Typical Pore Size / MWCO**	**Operating Pressure**	**Primary Objectives**	**Examples of Use**
Microfiltration (MF)	~0.1–1.4 µm (or >100,000 Da)	0.1–2 bar	Removal of bacteria, spores, large fat globules; isolation of casein micelles	Pasteurized milk preparation, fat standardization, reduction of bacterial load
Ultrafiltration (UF)	~10,000–100,000 Da	2–10 bar	Concentration of whey and casein proteins; removal of lactose and low-MW solutes	Production of WPC (40–80% protein), WPI (>90% protein), increased cheese yield
Nanofiltration (NF)	~100–1,000 Da	5–40 bar	Partial demineralization, removal of mono- and disaccharides; concentration of solids	Low-lactose milk production, partial demineralization of whey
Reverse Osmosis (RO)	~1–100 Da	30–100 bar	Near-total retention of dissolved solids; maximum concentration and water purification	Water recovery (closed loop), production of powdered dairy products

Microfiltration (MF). In dairy operations, MF is typically applied as a pretreatment step. It removes bacteria, spores, and large fat globules (diameter >1 μm), leading to a "clean," low-bacterial milk suitable for pasteurization or UHT processing [3]. MF also helps in defatting whey before protein concentration and in precise fractionation, such as separating casein micelles from whey proteins, which often requires ceramic membranes with pore sizes in the 0.1–0.2 μm range [4].

Ultrafiltration (UF). UF is a key process for protein enrichment in dairy liquids. It concentrates whey proteins (WPC with 35–80% protein, WPI >90%) and can boost cheese yield by returning UF retentate to the cheese milk [2]. UF also provides high selectivity by allowing lactose and salts to pass into the permeate while retaining the protein fraction.

Nanofiltration (NF) and Reverse Osmosis (RO). These processes are more "refined" in their separation range. They can partially or fully demineralize whey and reduce lactose levels, which is relevant for infant formulas or specialized products. RO can produce nearly powder-like dairy concentrates without the need for conventional evaporation, thus lowering energy consumption [1]. Both NF and RO filtrates may be reused in CIP (Cleaning-In-Place) or reintroduced into production if hygienic standards are maintained [3, 8].

Features of real industrial application include:

- **Energy demands and cost**: RO requires higher pressures and thus more energy; NF is an intermediate approach balancing energy input and demineralization efficiency [11].
- **Membrane costs**: ceramic membranes are more expensive but last longer under extreme conditions (high temperatures, aggressive cleaning agents) [6].
- **Scale-up considerations**: spiral-wound modules are compact and user-friendly in large-scale installations, while ceramic designs are bulkier but excel in processing heavily contaminated feeds [6].

One of the main challenges is the deposition of colloidal particles (proteins, fats, calcium salts) on the membrane surface, which reduces throughput and worsens selectivity [3, 8]. The main fouling mechanisms are:

- Formation of a gel layer from denatured proteins that can swell on the membrane surface;
- Microbial buildup (biofouling);
- Inorganic scaling by calcium salts and phosphates.

Concentration polarization, where solutes accumulate near the membrane surface, adds further resistance to flow. Strategies to mitigate these problems involve increasing cross-flow velocity, using turbulence promoters, periodic flow reversal, and implementing appropriate CIP procedures [8, 12].

Several standard approaches are used for membrane cleaning [13, 14]:

- **Alkaline (NaOH, NaOCl)**, which dissolves protein and fat deposits;
- **Acidic (HNO3)**, which targets inorganic salt deposits;
- **Enzymatic**, which provides gentler cleaning without severe pH shifts, especially critical for polymeric

membranes.

Successful cleaning extends membrane service life and supports stable operation in dairy processes [14].

Optimization of operating parameters can further help control fouling and maximize protein recovery [8, 14]:

- **Temperature**: Higher temperatures improve fluid viscosity and permeability but may denature proteins and promote fouling. Most MF/UF setups operate between 45 °C and 55 °C [4].
- **Pressure**: Excessive pressure sharply increases fouling and concentration polarization. Moderate values (e.g., 2–4 bar for UF) are commonly recommended.
- **Flow velocity**: High cross-flow velocities reduce polarization but demand greater energy for pumping and heating.

To enhance membrane performance, certain pretreatments are often carried out:

- **Defecation** (e.g., clarification, fat separation);
- **pH stabilization**, which is especially beneficial before NF or RO;
- **Diafiltration** (adding water to wash out soluble components such as lactose and salts).

Such steps reduce the likelihood of rapid fouling and improve selectivity toward protein fractions [3, 13]. As a result, carefully configured membrane processes—including the choice of materials, pore sizes, and optimal operating conditions—can effectively concentrate proteins and improve product quality in dairy applications.

3. Technological schemes and examples of membrane integration for protein enhancement

Membrane-based approaches offer versatile solutions for enhancing protein content in dairy products. By strategically combining methods such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), manufacturers can remove or retain specific components, reduce unwanted by-products, and ultimately add value to both primary dairy streams and secondary by-products [2, 8].

One of the main applications of membrane technology at the early stage of raw milk processing is microfiltration (MF) for:

- Bacterial defatting (reduction of total microorganisms and spores).
- Partial fat fractionation (removal of large fat globules >1 µm in diameter).

This results in “clean,” low-bacterial milk with more uniform fat content, which improves product safety and extends shelf life [3, 10]. Figure 1 illustrates a possible MF arrangement.

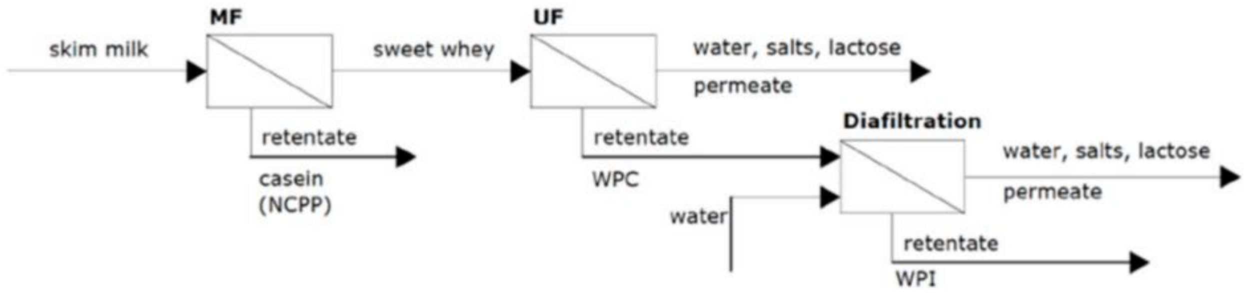

Figure 1: MF of skimmed milk to obtain NCPP and UF with diafiltration to obtain WPC and WPI from MF permeate. [2, 3].

Such a scheme may include the following stages:

- Preliminary separation of raw milk (for bulk fat removal);
- Microfiltration through a ceramic or polymeric membrane with pore sizes of about 0.14–0.8 µm (or an equivalent MWCO of ~100,000 Da) [14];
- Heating and pasteurization of the purified permeate, which can be bottled as fluid milk or further processed (homogenization, vitamin fortification, etc.).

A notable trend on the market is the production of “functional milk” with higher protein and reduced lactose content, often labeled as “UF milk” (ultrafiltered milk) [4]. The technology involves passing skim or partially skimmed milk through an ultrafiltration membrane (MWCO 10–100 kDa), retaining casein micelles and whey proteins in the retentate while allowing lactose and minerals to pass into the permeate. Some of the permeate (or water) can be redirected for diafiltration to further wash out lactose and mineral components. The final beverage may contain up to 6% total protein with lower overall carbohydrate content, which is particularly in demand in sports nutrition and products for consumers with mild lactose intolerance [1, 3].

Bridging these fluid milk applications to cheesemaking, it becomes clear that cheese yield strongly depends on the presence of casein micelles and whey proteins in the cheese curd. Applying UF before coagulation allows manufacturers to:

- Concentrate casein, because UF retains casein micelles while part of the lactose and minerals exit in the permeate;
- Reduce the loss of whey proteins, since they partially remain in the retentate, thus transferring more protein into the final cheese [2].

As a result, cheese yield increases, and the cheese structure becomes denser with improved ripening characteristics. To further lower lactose and mineral content in the cheese mass, processors often use diafiltration, which rinses the UF concentrate with pure water or UF permeate. This procedure helps to:

- Partially remove residual lactose, which is important for controlling acid development during cheese ripening;

● Develop a more stable, "clean" protein matrix suitable for specialty varieties (including those intended for dietary products) [2, 3].

Once milk coagulates, a by-product known as whey (either sweet or acid, depending on the cheesemaking process) emerges. It contains a significant proportion of whey proteins (β-lactoglobulin, α-lactalbumin), lactose, vitamins, minerals, and residual fat. To increase its value, the industry typically applies a sequence of membrane methods:

● MF for defatting (removal of fat globules) and clarification;
● UF or NF for concentrating whey proteins (WPC – whey protein concentrate, WPI – whey protein isolate) and partially demineralizing the feed [2, 3, 10].

This approach can yield high-protein products for the sports or confectionery markets, or specialized whey fractions for subsequent formulation. Historically, whey was considered a low-value by-product. However, membrane innovations have made it possible to obtain whey protein concentrates (WPC), ranging from 35% to 80% protein, and whey protein isolates (WPI) with over 90% protein [15, 16]. These can be used in functional beverages, ice cream, bakery goods, sports supplements, and clinical nutrition. Moreover, by carefully adjusting pH and temperature, processors can selectively isolate fractions such as β-lactoglobulin (notable for its gel-forming properties) and α-lactalbumin (used in infant formulas and for bioactive peptide synthesis) [3].

Membrane techniques, especially NF, can direct part of the lactose into the permeate, thereby reducing lactose in the final concentrate. If required, the permeate can undergo additional treatment via RO, enabling lactose crystallization for pharmaceutical or infant formula applications [11]. Furthermore, enzymatic hydrolysis of lactose into glucose and galactose, followed by the isolation of galacto-oligosaccharides (GOS), produces functional ingredients widely applied as prebiotics in the food industry [7].

In practice, a multi-stage arrangement comprising **MF + UF + NF/RO** is increasingly adopted:

● **MF** removes large fat droplets, bacteria, and particles (e.g., spores), resulting in a cleaner whey stream;
● **UF** concentrates protein and lowers lactose content in the permeate;
● **NF** partially demineralizes the solution and further reduces milk sugars if needed;
● **RO** finalizes the concentration to achieve high total solids or, alternatively, produces clean water for on-site reuse in a closed loop [2, 3].

Table 2 shows a representative example of the performance parameters before and after implementing this membrane cascade for 1000 L of whey:

Table 2: Example of changes in whey parameters using a multi-stage membrane process

Parameter	Initial Whey (1000 L)	After MF/UF	After NF/RO
Flow volume, L	1000	300–350 (retentate) + ~650–700 (permeate)	50–100 (concentrate) + ~250–300 (permeate)
Protein content, %	~1.0–1.2	5–8 in retentate (WPC)	Up to 10–12 (with further concentration)
Lactose content, %	~4.5–5.0	2–3 in retentate, some in permeate	<1–2 (can be crystallized thereafter)
Mineral content (ash), %	~0.6–0.8	0.4–0.5	0.1–0.3
Recovered water, L	—	—	up to 200–300 (depending on RO efficiency)

As shown in Table 2, implementing a multi-stage membrane arrangement not only raises the concentration of whey proteins but also yields RO permeate that can be reused, reducing natural resource consumption and wastewater volume [3, 10]. The economic advantages include lowering thermal energy demands (compared with evaporation) and broadening product ranges (WPC, WPI, lactose, mineral supplements).

In conclusion, membrane technologies offer numerous opportunities for processing dairy raw materials, from protein-enriched fluid milk to specialized whey products and high-value streams derived from side flows. Manufacturers who adopt these integrated systems gain a competitive advantage by optimizing raw material usage and expanding their product lines.

4. Conclusion

The analysis shows that membrane processes (MF, UF, NF, RO) provide a wide range of opportunities for enriching dairy products with protein and solving a number of related technological problems. In particular:

- Microfiltration allows efficient removal of fat and microorganisms, contributing to high quality milk for further processing.
- Ultrafiltration enables the concentration of both casein and whey proteins, increasing cheese yields and forming protein-enriched beverages (e.g. UF milk).
- Nanofiltration and reverse osmosis serve to partially or completely demineralize, reduce lactose and thicken the flow to high solids content. This opens up prospects for the use of permeates and retentates for

additional processing or reuse in the production cycle.

The implementation of complex schemes (e.g. combination of MF with UF and subsequent NF/RO) not only increases the protein value of the final product, but also contributes to resource saving (reduction of energy costs compared to evaporation, reduction of waste, water reuse). The most effective solutions are those with optimized operating parameters (temperature, pressure, flow rate) and carefully designed membrane cleaning modes (CIP), which together minimize the risk of fouling and ensure stable performance of the equipment.

Thus, membrane technologies form a reliable basis for the production of competitive high-protein dairy products, opening wide opportunities for increasing the economic efficiency of the industry and meeting current market demands.

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