Journal of Agriculture, Biology and Applied Statistics
Vol. 5, Nos. 1-2, 2026, pp. 21-30
© ARF India. All Right Reserved
URL: www.arfjournals.com
https://doi.org/10.47509/JABAS.2026.v05i01-02.02

Membrane Filtration Versus Vacuum Evaporation in Dairy Concentration: A Strategic Technical and Economic: Review

Aprna Sharma[1*] and Vedprakash Sahu[2]
[1],[2]Department of Dairy Technology, College of Dairy Science and Food Technology,*
Dau Shri Vasudev Chandrakar Kamdhenu Vishwavidyalaya (DSVCKV), Raipur, Chhattisgarh, India
**Corresponding Address: aprnasharma2696@gmail.com*

To Cite this Article

Aprna Sharma & Vedprakash Sahu (2026). Membrane Filtration Versus Vacuum Evaporation in Dairy Concentration: A Strategic Technical and Economic: Review. *Journal of Agriculture, Biology and Applied Statistics,* 5: 1-2, pp. 21-30.

Abstract: Water removal is an essential operation in dairy manufacturing, required to extend product shelf life, minimize bulk transport and storage volumes, and prepare liquid streams for spray drying or ingredient manufacturing. Traditionally, thermal vacuum evaporation has served as the workhorse of industrial concentration, capable of achieving high total solids content under continuous operation (Singh & Heldman, 2014). However, prolonged exposure to elevated temperatures induces structural modifications in milk proteins, degrades thermosensitive micronutrients, and imposes heavy thermal energy demands (Jeurnink& de Kruif, 1995; Anema & Li, 2003; Fox & McSweeney, 2015).

Pressure-driven membrane filtration operations—microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—have emerged as lower-temperature alternatives that maintain native nutrient functionality while lowering utility requirements (Cheryan, 1998; Pouliot, 2008). This review evaluates and compares the transport mechanisms, energetic demands, nutritional retention, economic drivers, and industrial applicability of both processing pathways. Current evidence indicates that while membrane systems reduce steam utility requirements and preserve bioactivity, vacuum evaporation remains necessary to reach the high solids thresholds demanded by downstream powder operations (Geankoplis, 2003; Singh & Heldman, 2014). Consequently, industrial processing is increasingly converging on hybrid process architectures, using reverse osmosis or ultrafiltration for pre-concentration followed by multi-effect vacuum evaporation (Daufin *et al*., 2001; Yee *et al*., 2009).

Keywords: Dairy concentration, membrane filtration, vacuum evaporation, energy efficiency, native proteins, hybrid processing

Received : 16 March 2026 • **Revised :** 14 April 2026 • **Accepted :** 25 April 2026 • **Published :** 19 October 2026

1. INTRODUCTION

Raw bovine milk contains approximately 87% water by mass, making fluid handling, thermal transport, and storage major logistical expenses across the global dairy supply chain (Walstra *et al*., 2006). Processing operations designed to remove water reduce bulk volume, extend shelf stability, and serve as foundational steps for manufacturing cheese, yogurt, milk protein concentrates (MPC), whey protein concentrates (WPC), sweetened condensed milk, and dried powders. By significantly reducing fluid volume prior to spray drying, water removal operations increase total processing throughput and operational efficiency across dairy manufacturing facilities.

For decades, vacuum evaporation has operated as the standard industrial method for large-scale water removal (Singh & Heldman, 2014). Operating under sub-atmospheric pressures lowers the boiling point of milk, mitigating extreme thermal damage compared to atmospheric boiling. Nevertheless, thermal evaporation relies on a complete phase change, consuming significant energy and risking thermal modifications to delicate constituents. Sustained exposure to heat alters delicate protein structures, reduces heat-sensitive vitamin activity, triggers Maillard browning reactions, and alters mineral equilibria within the fluid matrix (Jeurnink& de Kruif, 1995; Anema & Li, 2003; Fox & McSweeney, 2015).

To meet growing consumer demand for minimally processed, high-functionality dairy products, the dairy processing industry turned toward pressure-driven membrane filtration (Jelen, 1979; Saboya &Maubois, 2000). Operating without a phase change, pressure-driven membrane systems remove water at lower temperatures, preserving native protein structures, active enzymes, and volatile flavor compounds while dramatically reducing thermal energy requirements (Cheryan, 1998; Pouliot, 2008).

Modern processing utilizes four distinct membrane tiers: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). These technologies are defined by their pore size and molecular weight cut-off (MWCO), enabling precise separation of pathogens, proteins, lactose, minerals, or water (Brans *et al*., 2004; Blais *et al*., 2022). Reverse osmosis is widely used for bulk pre-concentration, whereas ultrafiltration is central to manufacturing high-protein ingredients (Zulewska *et al*., 2009).

Despite their advantages, membrane operations face distinct operational limitations, including membrane fouling, concentration polarization, hydraulic

pressure boundaries, and substantial capital outlay (Saxena *et al.*, 2009). As a result, membrane systems have not rendered thermal evaporation obsolete. Instead, modern processing plants increasingly combine both approaches into highly optimized hybrid processing arrangements (Daufin *et al.*, 2001; Yee *et al.*, 2009). This review evaluates and compares membrane filtration and vacuum evaporation across operational transport mechanisms, energy footprints, nutritional impacts, and industrial integration strategies.

2. MEMBRANE FILTRATION TECHNOLOGIES

Membrane filtration relies on hydraulic pressure differences across semi-permeable barriers to separate liquid dairy streams into distinct retentate and permeate fractions. Because these processes typically operate between 10 °C and 55 °C, heat-induced structural denaturation is effectively avoided, preserving native protein functionality and nutritional integrity (Cheryan, 1998; Fox & Brodkorb, 2008).

Separation Mechanisms and Classifications

The four primary membrane processes used in dairy processing are categorized by their physical separation capabilities and molecular cut-off levels:

- **Microfiltration (MF):** Possessing pore sizes between 0.1 µm and 10 µm, MF retains somatic cells, bacteria, and large fat globules while allowing proteins, lactose, and minerals to pass. It is routinely used for physical spore removal, extended shelf-life (ESL) fluid milk production, and fractionating micellar casein from native whey (Saboya & Maubois, 2000).
- **Ultrafiltration (UF):** Featuring MWCO values from 1 kDa to 100 kDa, UF retains casein micelles and globular whey proteins while permitting lactose and soluble minerals to permeate into the stream. UF is essential for producing milk protein concentrates (MPC), whey protein concentrates (WPC), and standardized cheese milk (Zulewska *et al.*, 2009; Blais *et al.*, 2022).
- **Nanofiltration (NF):** Operating at an MWCO range of 100 Da to 1000 Da, NF selectively retains lactose and multivalent ions (Ca^{2+}, Mg^{2+}) while allowing monovalent salts (Na^{+}, K^{+}) and water to pass. NF is widely deployed for partial demineralization and lactose concentration in whey streams (Atra *et al.*, 2005; Cuartas-Uribe *et al.*, 2009).

- **Reverse Osmosis (RO):** Utilizing dense, non-porous membranes, RO retains virtually all dissolved solutes, permitting only pure water transport under high hydraulic pressures (20 to 80 bar). It serves as an energy-efficient option for milk pre-concentration prior to downstream thermal treatment (Balde & Aider, 2017).

Operational Factors and Hydraulic Bottlenecks

Membrane performance is governed by transmembrane pressure, feed velocity, cross-flow shearing, and operating temperature (Geankoplis, 2003). Increasing processing temperatures decreases fluid viscosity, enhancing permeate flux; however, excessive temperatures risk thermal denaturation and accelerate fouling layer formation. Cross-flow configurations are universally adopted to provide shear forces along the membrane surface, controlling boundary-layer accumulation (Cheryan, 1998).

Membrane fouling remains the main operational hurdle limiting hydraulic efficiency. Adsorption of hydrophobic proteins, mineral scale formation (primarily calcium phosphate precipitation), and lipid deposition create resistant surface layers that reduce flux over time (Jeurnink& de Kruif, 1995; Saxena *et al*., 2009). Cleaning-in-place (CIP) regimens using sequential chemical treatments (alkaline wash for organics followed by acid wash for mineral scale) are required to restore operational flux, contributing to chemical waste and plant downtime (Tamime, 2008; Tang *et al*., 2010).

3. VACUUM EVAPORATION

Vacuum evaporation achieves water removal by supplying thermal energy to boil off water under reduced system pressure. Lowering system pressures reduces the boiling temperature of milk to between 45°C and 70°C, protecting product streams from the severe thermal stress of atmospheric boiling while maintaining high mass transfer rates (Singh & Heldman, 2014).

Thermal Operations and Energy Recovery

Unlike pressure-driven separation, thermal evaporation requires supplying the latent heat of vaporization to transition liquid water into steam. Because single-stage thermal evaporation is energy-intensive, commercial processing uses multi-effect evaporators. These systems pass secondary vapor generated in one effect into the

heating chest of the next operating effect at a lower pressure, maximizing thermal energy reuse across the system.

To further reduce thermal footprints, modern evaporators use advanced vapor recompression technologies:

- **Thermal Vapor Recompression (TVR):** High-pressure motive steam passes through a steam ejector to entrain and compress secondary vapor, reusing its latent heat to drive evaporation.
- **Mechanical Vapor Recompression (MVR):** Electric fans or compressors mechanically raise the pressure and temperature of outgoing secondary vapor, recycling it back as the primary heating medium without requiring continuous live steam feeds during steady-state operation.

MVR evaporator configurations significantly lower utility requirements, making high-solids concentration economically viable for large-scale operations (GEA Group, 2021).

Technological Reach and Limitations

Despite thermal efficiency improvements, heating fluid streams can lead to distinct changes in milk components. Denatured β-lactoglobulin complexing with κ-casein on casein micelle surfaces can alter stream viscosity and gelation properties (Anema & Li, 2003; Fox & McSweeney, 2015). Extended thermal exposure can also degrade thermosensitive vitamins and foster Maillard reactions that alter color and flavor profiles (Fox & McSweeney, 2015). Additionally, protein aggregation and mineral precipitation on heat-exchanger surfaces lower heat-transfer efficiency over extended runs, requiring systematic CIP intervention (Jeurnink & de Kruif, 1995; Tang *et al.*, 2010).

Despite these factors, vacuum evaporation remains essential for reaching total solids concentrations above 50%, which is necessary prior to entering spray dryers (Singh & Heldman, 2014).

4. COMPREHENSIVE TECHNICAL & ECONOMIC COMPARISON

A direct comparison of membrane filtration and vacuum evaporation demonstrates distinct operational trade-offs across separation dynamics, energy footprints, product quality, and system limits.

Table 1: Key Parameter Comparison of Concentration Pathways

Operational Metric / Parameter	*Membrane Filtration Operations*	*Thermal Vacuum Evaporation*	*Primary Supporting References*
Primary Separation Drive	Pressure-driven mass transport	Thermal phase change (vaporization)	Cheryan (1998); Singh & Heldman (2014)
Operating Thermal Regime	Low temperature (10–55 °C)	Moderate temperature (45–70 °C)	Pouliot (2008); Zulewska et al. (2009)
Primary Energy Source	Electrical power (hydraulic pumps)	Thermal energy (steam) / Electrical (MVR)	Atra et al. (2005); GEA Group (2021)
Energy Consumption Efficiency	Extremely high for initial water removal	Moderate to high (optimized via MVR/TVR)	Atra et al. (2005); Yee et al. (2009)
Protein Denaturation Extent	Minimal to negligible	Moderate to high (β-lg / κ-casein complexing)	Anema & Li (2003); Fox & Brodkorb (2008)
Vitamin Retention Rate	High (preserves B-complex, Vitamin C)	Moderate (thermal loss over residence time)	Fox & McSweeney (2015)
Maximum Solids Ceiling	Restricted to ~20–25% Total Solids	Capable of reaching 50–60%+ Total Solids	Geankoplis (2003); Singh & Heldman (2014)
Primary Mass Transfer Barrier	Membrane fouling, osmotic head	Heat exchanger scaling, Maillard reactions	Jeurnink& de Kruif (1995); Tang et al. (2010)
Operational Cleaning Requirements	Chemical CIP (alkaline/ acid sequence)	Thermal/Chemical CIP for heat burn-on	Tamime (2008); Tang et al. (2010)
Capital Outlay vs. Footprint	Moderate capital, compact modular area	High capital, large vertical physical footprint	Daufin et al. (2001); Saxena et al. (2009)

Energy Efficiency and Economic Factors

Membrane reverse osmosis operates without a phase transition, making it significantly more energy efficient per mass of water removed than thermal evaporation during initial concentration stages (Atra *et al.*, 2005). Because the latent heat of vaporization ($2260\ kJ/kg$) does not need to be supplied, the mechanical energy required by high-pressure pumps in RO operations is only a fraction of the thermal energy needed for evaporators.

However, as solute concentrations rise, exponential increases in osmotic pressure and fluid viscosity create severe mechanical boundaries for pumps and membrane modules (Geankoplis, 2003). When concentrated skim milk approaches 20% to 25% total solids, osmotic pressure exceeds commercial pump thresholds (often required to operate above 60 to 80 bar), causing permeate flux to decline dramatically.

Conversely, vacuum evaporators handle viscous feed fluids effectively, raising total solids to 50–60% without mechanical overload. Combining reverse osmosis pre-concentration ahead of thermal evaporation can lower boiler steam requirements by 30% to 60%, optimizing overall utility expenses and boiler capacity (Atra *et al.*, 2005; Yee *et al.*, 2009).

Low Solids Concentration Stage (<20% Total Solids): Membrane filtration is the economically superior technology. It avoids latent heat input, consumes significantly lower energy per unit of water removed, protects thermosensitive micronutrients, and achieves high mass-reduction throughput.

High Solids Concentration Stage (>50% Total Solids): Thermal vacuum evaporation becomes indispensable. It overcomes osmotic pressure limitations, efficiently processes fluid with rising bulk viscosity, and lowers moisture content to the exact levels required for spray drying feed systems.

Nutritional Quality and Protein Functionality

Processing dairy streams below protein denaturation thresholds preserves native globular structures, retaining key functional properties such as solubility, foaming capacity, emulsification, and heat-induced gelation (Fox & Brodkorb, 2008; Zulewska *et al.*, 2009). Native whey proteins (such as α-lactalbumin and β-lactoglobulin) remain fully soluble when processed via ultrafiltration or reverse osmosis under mild thermal regimes.

In contrast, vacuum evaporation exposes streams to elevated temperatures over extended residence times. Heat treatment causes whey proteins to unfold, exposing hydrophobic groups and facilitating covalent bonding with κ-casein on the surfaces of casein micelles (Anema & Li, 2003; Fox & McSweeney, 2015). While this can be advantageous for specific end-products like yogurt, it compromises protein solubility and alters gelation behavior in spray-dried protein concentrates. Vacuum evaporation can also lead to measurable losses in heat-sensitive micronutrients like folate and vitamin C (Fox & McSweeney, 2015).

5. INDUSTRIAL INTEGRATION AND HYBRID PROCESSING

To address the individual limitations of membrane filtration and thermal evaporation, modern dairy processing plants increasingly rely on integrated hybrid processing systems (Daufin *et al.*, 2001). Combining membrane pre-concentration with multi-effect or MVR vacuum evaporation maximizes energy efficiency, preserves native protein functionality, and maintains high throughput capacities.

Industrial implementations demonstrate clear operational roles across processing stages:

- **Milk and Whey Pre-Concentration:** Reverse osmosis units remove bulk water up to approximately 20% total solids, reducing stream volume by up to 60–70% before entering multi-effect evaporators. This pre-concentration step significantly cuts steam requirements in the evaporator stage (Atra *et al*., 2005; Yee *et al*., 2009).
- **Fractionation and Protein Standardization:** Microfiltration and ultrafiltration fractionate caseins, enrich whey protein concentrates (yielding WPC34 to WPC80 products), and standardize cheese milk without thermal degradation (Saboya &Maubois, 2000; Zulewska *et al*., 2009; Blais *et al*., 2022).
- **High-Solids Finishing:** Vacuum evaporators concentrate pre-filtered streams from 20% total solids to over 50% total solids, achieving the exact fluid viscosity and physical stability required for downstream spray drying systems (Singh & Heldman, 2014; GEA Group, 2021).

Integrated hybrid designs help processing plants optimize overall utility usage, lower thermal energy costs, increase total plant throughput, and maintain native product quality (Yee *et al*., 2009).

6. CONCLUSIONS

Membrane filtration and vacuum evaporation serve complementary roles in modern dairy concentration. Membrane processes excel in initial water removal and product fractionation, operating at lower temperatures with high energy efficiency while preserving native protein structures and heat-sensitive nutrients. However, exponential increases in osmotic pressure and fluid viscosity cap their maximum concentration threshold at 20–25% total solids.

Vacuum evaporation remains essential for reaching the high solids concentrations (>50% total solids) required for powder production and specialized concentrated products. Combining both technologies into hybrid systems—using reverse osmosis or ultrafiltration for pre-concentration followed by multi-effect vacuum evaporation—provides a balanced, highly effective approach to energy efficiency, product quality, and operational throughput in modern dairy manufacturing.

REFERENCES

Anema, S. G., & Li, Y. (2003). Association of denatured whey proteins with casein micelles in heated reconstituted skim milk and its effect on casein micelle size. *Journal of Dairy Research*, 70(1), 73–83.

Atra, R., Vatai, G., Bekassy-Molnar, E., & Balint, A. (2005). Investigation of ultra- and nanofiltration for utilization of whey protein and lactose. *Journal of Food Engineering*, 67(3), 325–332.

Balde, A., & Aider, M. (2017). Effect of skim milk concentration by reverse osmosis, cryoconcentration and vacuum evaporation on its physicochemical and technological properties. *International Journal of Food Science & Technology*, 52(7), 1572–1580.

Blais, H. N., Schroën, K., & Tobin, J. T. (2022). A review of multistage membrane filtration approaches for enhanced efficiency during concentration and fractionation of milk and whey. *International Journal of Dairy Technology*, 75(4), 749–760.

Brans, G., Schroen, C. G. P. H., Van der Sman, R. G. M., & Boom, R. M. (2004). Membrane fractionation of milk: State of the art and challenges. *Journal of Membrane Science*, 243(1–2), 263–272.

Cheryan, M. (1998). *Ultrafiltration and microfiltration handbook* (2nd ed.). Technomic Publishing.

Cuartas-Uribe, B., Bes-Piá, M. C., Mendoza-Roca, J. A., &Alcaina-Miranda, M. I. (2009). Lactose separation from whey via nanofiltration. *Desalination*, 241(1–3), 244–250.

Daufin, G., Escudier, J. P., Carrère, H., Bérot, S., Fillaudeau, L., &Decloux, M. (2001). Recent applications of membrane technology in the agri-food industry. *Innovative Food Science & Emerging Technologies*, 2(2), 89–102.

Fox, P. F., & Brodkorb, A. (2008). The casein micelle: Historical aspects, current concepts and significance. *International Dairy Journal*, 18(7), 677–684.

Fox, P. F., & McSweeney, P. L. H. (2015). *Advanced dairy chemistry: Volume 1A: Proteins* (4th ed.). Springer.

GEA Group. (2021). *Evaporation technology for the dairy industry*. GEA Group.

Geankoplis, C. J. (2003). *Transport processes and separation process principles* (4th ed.). Prentice Hall.

Jelen, P. (1979). Industrial applications of membrane processes in the dairy industry. *Food Technology*, 33(10), 56–64.

Jeurnink, T. J. M., & de Kruif, C. G. (1995). Calcium phosphate precipitation during milk concentration by heating. *Netherlands Milk and Dairy Journal*, 49, 369–390.

Pouliot, Y. (2008). Membrane processes in dairy technology: From classical to advanced applications. *Journal of Agricultural and Food Chemistry*, 56(12), 4293–4303.

Saboya, L. V., &Maubois, J. L. (2000). Current developments of microfiltration technology in the dairy industry. *Lait*, 80(6), 541–553.

Saxena, A., Tripathi, B. P., Kumar, M., & Shahi, V. K. (2009). Membrane-based techniques for the separation and purification of proteins: An overview. *Advances in Colloid and Interface Science*, 145(1–2), 1–22.

Singh, R. P., & Heldman, D. R. (2014). *Introduction to food engineering* (5th ed.). Academic Press.

Tamime, A. Y. (Ed.). (2008). *Cleaning-in-place: Dairy, food and beverage operations* (3rd ed.). Blackwell Publishing.

Tang, X., Flint, S. H., Brooks, R. J., & Bennett, R. J. (2010). The cost of cleaning-in-place in dairy processing plants. *Journal of Cleaner Production*, 18(12), 1124–1129.

Walstra, P., Wouters, J. T. M., & Geurts, T. J. (2006). *Dairy science and technology* (2nd ed.). CRC Press.

Yee, K. W., Wiley, D. E., & Bao, J. (2009). Dynamic optimization of industrial reverse osmosis milk concentration plants. *Desalination*, 236(1–3), 250–256.

Zulewska, J., Newbold, M., & Barbano, D. M. (2009). Efficiency of protein standardization by ultrafiltration in dairy processing. *Journal of Dairy Science*, 92(2), 554–564.