Use of Polymeric and Ceramic Membranes for Dairy Wastewater Treatment: A Review

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Abstract:
Dairy processing produces wastewater with high organic loads (proteins, lactose, fats), suspended solids, and variable composition linked to production activities. Membrane technology provides compact, high-quality treatment and is increasingly being considered for water reuse and resource recovery. Ceramic membranes made of oxides such as alumina, zirconia, and titania offer significant advantages over polymeric membranes: chemical and thermal robustness, mechanical strength, and tolerance to aggressive cleaning. This descriptive paper synthesizes the state of knowledge on the use of ceramic membranes on dairy wastewater, focusing on membrane types and configurations, fouling mechanisms, cleaning strategies, operational methods, and economic considerations. The paper outlines specific pilot or plant-scale configurations, performance metrics used in the literature, and practical recommendations for implementing ceramic-membrane-based systems in dairy plants. The goal is to present a clear, practical context that researchers and practitioners can use to design pilots, anticipate operational challenges, and evaluate lifecycle tradeoffs.
Keywords: Dairy processing industry, Dairy wastewater, Membrane technologies, Polymeric membranes, Ceramic membranes.

Introduction

Dairy processes produce a variety of wastewater streams - from high-strength whey and product wash water to clean-in-place (CIP) wastewater. Typical characteristics include high biochemical oxygen demand (BOD/COD), increased suspended solids (TSS), fats, oils and greases (FOG), soluble proteins and sugars (lactose), and intermittent high-strength discharges linked to production schedules. Traditional biological processes (activated sludge, anaerobic digesters) are widely used, but membrane technologies are attractive for their small footprint and ability to provide consistent wastewater quality for reuse, discharge compliance, or downstream concentration and assessment.

Ceramic membranes have attracted attention in food and dairy applications because they tolerate high temperatures and aggressive chemicals, enabling more effective clean-in-place (CIP) operations and potentially longer membrane life. Their mechanical robustness makes them suitable for tubular and monolithic module geometries used in industrial settings. However, ceramic membranes have a higher initial cost than polymeric alternatives and can be susceptible to fouling by proteins and lipids if upstream pretreatment is inadequate. This paper provides a descriptive review of ceramic membrane types and configurations, the mechanisms and dynamics of fouling in dairy streams, cleaning and operational strategies, performance metrics, and economic considerations then synthesizes practical recommendations for implementation.

Sources of Dairy Waste Water:

Milk Processing Activities:

Cleaning of equipment, tanks, and pipelines.

Spillage and washing during milk reception and storage.

Losses during pasteurization and packaging processes.

Production of Dairy Products:

Butter, cheese, and yogurt manufacturing generates wastewater from washing, rinsing, and product spillage.

Serum (whey) drainage during cheese production.

Cleaning Operations:

Cleaning-in-Place (CIP) systems and floor washing.

Detergents, sanitizers, and water contribute to the effluent load.

Utilities:

Boiler and cooling tower blow down. Water softener regeneration discharge.

Miscellaneous Sources:

Effluent from ancillary operations like ice cream production, milk powder manufacturing, and flavored milk production.

Domestic wastewater from worker facilities within the dairy plant.

Characteristic of the Dairy Effluent:

1. Physical Characteristics:

High Suspended Solids (SS): Includes milk residues, fats, and sediments.

Turbidity: Caused by milk solids, cleaning agents, and organic matter.

Color: Often white or grayish due to milk residues and detergents.

2. Chemical Characteristics:

High Biochemical Oxygen Demand (BOD): Ranges from 1,500 to 4,000 mg/L due to the presence of organic matter like milk proteins, lactose, and fats.

High Chemical Oxygen Demand (COD): Ranges from 2,500 to 10,000 mg/L, depending on the processes.

pH Levels: Varies from acidic (from whey discharge) to alkaline (due to detergents and cleaning chemicals), typically between 4.5 and 11.

Fat, Oil, and Grease (FOG): Significant levels due to milk fats.

Nutrients: Contains nitrogen and phosphorus, mainly from proteins and cleaning agents.

Chlorides and Sulfates: From detergents and sanitizing chemicals.

3. Biological Characteristics:

High Organic Load: Supports microbial growth, potentially leading to rapid degradation and odor formation.

Pathogenic Microorganisms: Possible presence of bacteria, depending on hygiene standards and wastewater handling.

Soil contamination and odor issues.

Corrosion and clogging of drainage systems from fats and solids.

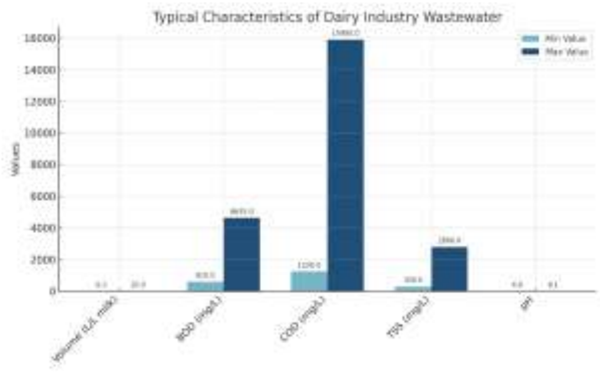

Figure 1: Typical Characteristics of Dairy Industry Wastewater

Dairy Waste Water Treatment:

Dairy Industry Wastewater Treatment are:

Remove organic matter, nutrients, and pathogens.

Meet regulatory standards for effluent discharge.

Water reuse and recycling opportunities.

Treatment methods generally used in dairy industry are the following.

Mechanical Treatment: This is the initial phase of the dairy waste treatment and involves screens, grit chambers, skimming tank or sedimentation tank.

Chemical Treatment: Chemical treatment involves the technique of precipitation.

Biological Treatment: Biological treatment often referred to as secondary treatment is used to remove materials left after primary treatment.

Advanced Technologies for Dairy Effluent Treatment:

- Electrocoagulation
- Adsorption
- Membrane Treatment
- Aerobic Treatment
- Anaerobic Treatment

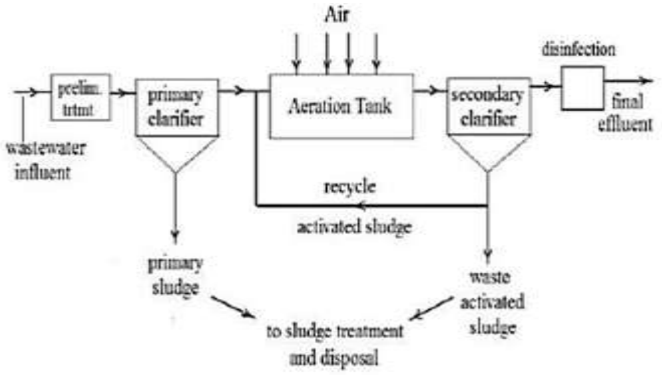

Figure 2: Flowchart showing treatment of dairy processing wastewater

A series of steps are followed at the dairy wastewater treatment plant:

Preliminary Treatment: The first step in treating dairy wastewater is to remove large solids and debris. This may include:

Screening: to filter out large particles like food scraps and debris.

Sedimentation: allowing larger solids to settle at the bottom of a tank.

Primary Treatment: The primary treatment focuses on removing suspended solids and reducing the organic load in the wastewater. Common techniques include:

Settling tanks: where heavier solids are allowed to settle to the bottom.

Floatation systems: to remove lighter substances like fats and oils.

This stage significantly reduces the Biological Oxygen Demand (BOD) but may not be sufficient for full treatment.

Secondary Treatment (Biological Treatment): Secondary treatment uses biological processes to degrade the organic matter remaining in the wastewater. Common methods include:

Activated Sludge Systems: aerating the wastewater to promote the growth of microorganisms that consume the organic pollutants.

Trickling Filters: a biological filter system that allows wastewater to flow over a bed of microbial biofilm, which breaks down organic matter.

Rotating Biological Contactors (RBC): rotating disks covered with microorganisms that treat the wastewater as it passes through.

This stage helps reduce BOD, total suspended solids (TSS), and some nutrients like nitrogen and phosphorus.

Tertiary Treatment: This stage involves advanced methods to further treat the wastewater to meet regulatory standards and improve the quality of the effluent. It may include:

Nutrient removal: to reduce nitrogen and phosphorus levels, which can contribute to eutrophication in receiving water bodies?

Filtration and disinfection: using methods like sand filtration, UV radiation, or chemical disinfectants to remove pathogens and ensure water quality.

Sludge Management: The solids removed during treatment, known as sludge, require further processing. This can involve:

Thickening: to concentrate the sludge.

De-watering: to reduce its moisture content.

Anaerobic digestion: which can break down the organic matter in the sludge and produce biogas (methane), offering a sustainable way to manage waste and recover energy.

Components of Dairy Wastewater:

Dairy wastewater contains various pollutants, such as:

- Organic matter (from milk, cream, whey, and other dairy products)
- Fatty acids and oils (from milk fat)
- Proteins (such as casein and whey proteins)
- Nutrients (mainly nitrogen and phosphorus)
- Solids (both suspended and dissolved)
- Microorganisms and pathogens (bacteria and viruses)
- High Biological Oxygen Demand (BOD), which is an indicator of organic pollution

Importance of Dairy Wastewater Treatment

Environmental Protection: Proper treatment prevents the contamination of water bodies and helps maintain biodiversity.

Compliance with Regulations: Many countries have strict laws regarding wastewater discharge quality, and treating dairy wastewater ensures compliance with these standards.

Resource Recovery: With advanced treatment, dairy wastewater can be reused for non-potable purposes (such as irrigation or cooling), reducing the demand for fresh water.

Challenges in Dairy Wastewater Treatment

High Variability: Dairy wastewater can vary greatly in composition depending on the type of dairy products being processed, making treatment challenging.

High Organic Load: The presence of high levels of organic matter requires effective biological treatment systems.

Fats and Oils: Dairy wastewater often contains fats and oils that can cause issues in treatment systems, such as clogging or reduced efficiency.

Treatment Process for Dairy Wastewater:

Treatment processes for dairy wastewater include removal of solids, oils and fats by primary techniques, removal of organic matter and nutrients by secondary techniques and polishing by tertiary techniques.

The choice of technology to manage dairy wastewater depends on factors such as the volume and characteristics of the wastewater, the availability of resources and local regulations. It is essential to know the composition of the wastewater before properly designing any dairy wastewater treatment plant.

The various technologies can be used to achieve the desired level of effluent treatment and reuse or discharge of dairy industry such as : Physicochemical treatment, Anaerobic digestion, Aerobic treatment, Membrane filtration, Advanced oxidation etc.

In membrane technology Hollow Fiber Polymeric and Ceramic Membrane are suitable for different treatment/separation processes.

Membrane Filtration Technology:

Membrane separation plays an important role in waste water treatment.

The common membrane separation processes like microfiltration, ultrafiltration, nanofiltration, reverse osmosis and electrodialysis are used to remove contaminants from dairy waste water.

These technologies can be effective in producing high quality effluent for reuse or discharge.

Among the various membrane based treatment options for reducing the COD of effluent from dairy industry, Microfiltration Processes are more economical than the other (RO/NF/UF) processes in terms of achieving a high flux with a low energy input.

Membranes can be used at different stages of the production process in the dairy industry.

The effluent from the dairy industry can consist of milk, whey, detergents, cleaning products in general, production residues, dyes, flavorings, among others.

The main objective of using membranes is to separate molecules in suspension or solution by their molecular weight, using different membranes produced with different materials.

The types of membranes can be split into two main groups – Polymeric (Organic) and Ceramic (Inorganic).

Polymeric Membranes:

Polymeric membranes include a range of different membrane types such as spiral wound, hollow fiber and flat sheet (plate-and-frame) membranes - all of which are made from organic materials.

Polymeric spiral wound membranes provide a high membrane area per element, leading to a reduced footprint and cost-efficient plant designs.

Cleaning of these types of membranes requires specially formulated cleaning detergents to extend their lifetime.

As polymeric membranes come in a wide range of pore sizes, they can be used for a large number of dairy filtration applications from RO to MF.

Figure 3: Polymeric Membranes

Ceramic membranes:

Figure 4: Ceramic membranes

Ceramic membranes are inorganic porous structures usually manufactured from metal oxides such as alumina (Al_2O_3), zirconia (ZrO_2) and titania (TiO_2). They are available in microfiltration (MF) and ultrafiltration (UF) pore sizes and are configured as:

Tubular modules: Straight or corrugated tubes; commonly used in wastewater because they handle abrasive feeds and allow straightforward CIP.

Monolithic (honeycomb) structures: High packing density and mechanical strength; used where compactness is needed.

Flat-sheet and plate-and-frame: Less common for aggressive industrial wastes.

Typical operation modes include crossflow filtration (to minimize cake buildup), periodic backwash or backflush for physically reversible fouling, and CIP routines using alkaline, acidic or enzyme-based chemistries.

Advantages of ceramic membranes:

- High thermal resistance (allows hot CIP or sterilizing conditions).
- Chemical resistance (suitable for high-pH and low-pH cleaners and oxidants).
- Mechanical strength (withstand high shear or transients).
- Potentially long service life with stable pore structure.

Limitations include higher upfront cost (membrane material and module manufacturing) and brittle behavior that requires careful mechanical design and handling.

Dairy wastewater characteristics relevant to membrane treatment

Dairy wastewater components that influence membrane performance:

Proteins: Tend to adsorb on surfaces and cause pore blocking and irreversible fouling.

Fats & oils (lipids): Form hydrophobic deposits and emulsions that form tenacious cakes.

Suspended solids: Milk solids and precipitates create cake layers that increase hydraulic resistance but are often reversible.

Soluble organic matter (SMP/EPS if biological processes involved): Contribute to sticky, gel-like fouling layers.

pH and temperature variation: CIP and cleaning cycles alter conditions significantly.

Because of these constituents, successful membrane deployment commonly requires upstream physical/chemical pretreatment steps (screening, dissolved air flotation (DAF), coagulation/flocculation, fat traps) to limit heavy fouling loads.

Fouling mechanisms and dynamics in ceramic membranes

Fouling in dairy wastewater follows familiar patterns described for other organic-rich streams but with dairy-specific signatures:

1. **Initial adsorption and pore blocking:** Soluble proteins and small organics enter pores and adsorb, resulting in pore constriction or irreversible resistance.
2. **Cake layer formation:** Suspended solids and aggregated proteins/fats form a cake on the membrane surface; often reversible by physical cleaning (backwash, shear).
3. **Hydrophobic foulant deposition:** Lipids and emulsified fats form cohesive layers that resist hydraulic cleaning and require surfactant or enzymatic treatment.
4. **Biofouling (if biological content present):** Growth of biofilms (EPS/SMP) may occur downstream of biological pre-treatment and contribute to fouling permanence.

Understanding the relative contribution of reversible (cake) and irreversible (adsorption/pore blocking) fouling is critical. Typical diagnostic tools in studies include flux/TMP monitoring, resistance-in-series analysis, Hermia model fitting (to infer dominant fouling mechanisms), chemical oxygen demand (COD) partitioning, SEM imaging of fouled surfaces, ATR-FTIR for foulant chemistry, and extraction/analysis of EPS/SMP.

Cleaning strategies and best practices

Ceramic membranes permit a wide range of cleaning strategies because of their chemical/thermal tolerance:

Physical cleaning: Periodic backwashing/backflushing, high crossflow velocity, and air-scouring (for tubular modules) are first-line operations to remove reversible cake layers.

Chemical CIP: Alkaline cleaners (e.g., NaOH) dissolve and desorb proteins and organic matter; acidic cleaners (e.g., HCl) remove inorganic scaling; surfactants or chelating agents may help remove lipids and metal complexes. Ceramics can tolerate higher alkalinity, temperature, and oxidants (e.g., NaOCl at controlled concentrations) than many polymeric membranes.

Enzymatic pretreatment/CIP: Proteases (for proteins) and lipases (for fats) are effective in breaking down organic foulants; enzymatic steps are often used as targeted cleaning or pretreatment when protein/lipid fouling dominates.

Operational strategies to reduce fouling frequency: Lower operating fluxes, intermittent high-shear scouring, staged coagulation/flocculation upstream, and DAF for FOG removal.

Performance metric is **flux recovery ratio (FRR)** after cleaning cycles and cumulative FRR over time indicates whether irreversible fouling accumulates.

Typical pilot configuration for a dairy:

A typical ceramic membrane treatment train in a dairy plant may include:

Coarse screening and grease traps: Remove large solids and free oils.

Equalization tank: Dampens variability in flow and strength.

Pretreatment (optional): Coagulation/flocculation or DAF to remove emulsified fats and fine solids.

Ceramic MF/UF modules: Operated in crossflow; periodic backwash and CIP schedule.

Polishing (NF/RO) or disinfection: If high-quality reuse water is required (e.g., for CIP water or boiler feed).

Concentrate handling: Recovered solids (concentrate) can be valorized or further treated (e.g., anaerobic digestion for energy recovery).

Design fluxes for MF/UF in dairy applications commonly are conservative (for example 20–80 $L \cdot m^{-2} \cdot h^{-1}$ depending on feed quality and module type) to balance throughput and fouling rates.

Performance indicators and monitoring

Essential parameters and monitoring practices:

Hydraulic: Permeate flux ($L \cdot m^{-2} \cdot h^{-1}$), transmembrane pressure (TMP), feed and permeate flowrates.

Water quality: COD/BOD, TSS, turbidity, FOG, protein concentration, conductivity, pH.

Fouling diagnostics: Rt (total resistance), Rrev/Rirr (reversible/irreversible resistance), FRR after CIP, SEM and ATR-FTIR snapshots.

Operational logs: CIP chemical volumes, temperatures, durations, frequency, downtime and labour times.

Economic: Energy consumption (kWh), chemical consumption (kg or L), membrane replacement intervals and costs, capex breakdown.

Regularly recording these allows linking fouling evolution to operating conditions and supports techno-economic analysis.

Economic and lifecycle considerations:

Economic comparison versus polymeric membranes requires life-cycle thinking:

CAPEX: Ceramic modules historically cost more per unit area than polymeric membranes and require robust skids and installation.

OPEX: Ceramics may demand higher pumping energy depending on design, but often incur lower replacement frequency and more aggressive/shorter CIP cycles (because cleaning is more effective), leading to reduced membrane replacement costs and possibly lower long-term chemical costs.

Membrane lifetime: Ceramics can last substantially longer (multi-year to decades in many installs) if mechanical stresses and handling are controlled.

Downtime & labour: More aggressive CIP tolerance reduces unplanned downtime and labor intensity of membrane changeouts.

A comprehensive assessment uses LCOW (levelized cost of water), NPV and sensitivity analyses on membrane price, lifetime, energy and chemical costs to determine break-even points for ceramic adoption. The viability improves when high-temperature or aggressive cleaning is required, when membrane replacements are costly or disruptive, or when recovered water has high value (internal reuse).

Conclusion:

Ceramic membranes offer compelling operational strengths for dairy wastewater treatment especially where aggressive cleaning, elevated temperatures or long service life are priorities. Their key challenges remain higher upfront cost and managing organic (protein/lipid) fouling. With appropriate pretreatment, conservative flux design, and optimized CIP (including targeted enzymatic or surfactant approaches), ceramics can deliver reliable, high-quality effluent suitable for reuse and can be economically favorable over the system lifetime for medium-to-large dairies. Implementers should prioritize pilots, thorough monitoring, and techno-economic modeling tailored to local costs and operational patterns to determine the right choice for their facility.

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