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Dairy Industry Waste Water Treatment Using a Simple Membrane Setup

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Abstract:
This study investigates the treatment of dairy-industry wastewater using a simple, single-stage ultrafiltration (UF) system equipped with polyether sulfone (PES) and polyvinylidene fluoride (PVDF) membranes under laboratory-scale conditions. The influent exhibited high organic loading (COD ≈ 3,950 mg L^{-1}, BOD_5 ≈ 1,750 mg L^{-1}), characteristic of small dairy effluents. System performance was evaluated in terms of permeate flux, contaminant removal, and fouling behavior. Optimum operation was achieved at a transmembrane pressure of 2 bar, yielding average COD and TSS removal efficiencies of 78 % and 97 % for PES, and 73 % and 95 % for PVDF, respectively. Flux decline was primarily reversible, governed by cake-layer formation, and effectively mitigated through a two-step NaOH–citric acid cleaning protocol restoring over 90 % of the initial flux. The system operated with low specific energy demand (0.35 kWh m^{-3}) and treatment cost (≈ 0.28 USD m^{-3}), highlighting its potential for decentralized and small-scale dairy applications. The results confirm that simplified UF setups can deliver reliable effluent quality, operational stability, and economic feasibility for sustainable wastewater management in the dairy sector.

Keywords:
Dairy wastewater; ultrafiltration; PES membrane; PVDF membrane; fouling; flux recovery; transmembrane pressure; wastewater reuse; sustainable treatment; membrane cleaning.

A. INTRODUCTION

a. Background on Dairy Industry Wastewater

Overview of Dairy Industry and Its Wastewater Generation

The dairy industry represents one of the most water-intensive sectors of the food-processing chain, consuming between 1 and 10 litres of water per litre of milk processed [1], [7]. Water is required for pasteurization, cleaning-in-place (CIP) operations, cooling, and rinsing, leading to effluent volumes typically reaching 2–3 times the amount of processed milk [1]. As global milk production continues to rise, the associated wastewater load increases proportionally, driving an urgent need for sustainable treatment strategies.

Characteristics of Dairy Industry Wastewater

Dairy wastewater is characterized by high concentrations of organic matter (chemical oxygen demand > 3,000 mg L^{-1}), suspended solids, fats, oils, proteins, and lactose [2], [8], [13]. Its composition fluctuates with product type and cleaning frequency, typically exhibiting pH values between 4.5 and 8.5 and biological oxygen demand (BOD_5) ranging from 1,000 to 2,500 mg L^{-1} [6]. These features render the effluent highly biodegradable but susceptible to rapid anaerobic degradation if untreated, releasing odorous gases and causing oxygen depletion in receiving waters [18].

Environmental Impacts of Untreated Dairy Wastewater

Direct discharge of untreated dairy effluent leads to eutrophication, depletion of dissolved oxygen, and aesthetic degradation of water bodies [1], [15]. Nutrient-rich components (mainly nitrogen and phosphorus) contribute to algal blooms, while high organic loads impose severe stress on aquatic ecosystems [23]. Regulatory frameworks worldwide have tightened permissible discharge limits, compelling dairy processors, especially small and medium enterprises to seek compact, cost-effective solutions [4], [29].

b. Current Treatment Methods and Their Limitations

Conventional Treatment Processes

Traditional treatment methods include primary screening, dissolved-air flotation, and biological processes such as activated sludge or anaerobic digestion [18], [21]. While biological systems effectively reduce BOD and COD, they are sensitive to load fluctuations and produce large volumes of secondary sludge [7]. Coagulation–flocculation using chemical or natural coagulants (e.g., *Moringa oleifera*) has been applied as a pretreatment to improve settleability [25].

Challenges in Treating Dairy Industry Wastewater

Despite advances, conventional methods often fail to meet stringent reuse standards due to incomplete removal of fine colloids, lipids, and proteins [2], [19]. High variability in wastewater composition causes inconsistent effluent quality, and sludge disposal remains costly [23]. Biological treatment efficiency decreases under low-temperature conditions common in temperate regions [18]. These challenges underscore the need for more robust and easily controllable systems.

Need for Improved Treatment Technologies

Membrane-based processes have emerged as attractive alternatives due to their compact design, scalability, and superior effluent quality [7], [20]. Ultrafiltration (UF) in particular can effectively remove macromolecules and suspended solids without requiring chemical additives [1], [2]. However, the widespread application of UF in small dairies is hindered by fouling, energy demand, and membrane replacement costs [17], [29]. Research now focuses on developing simplified, low-maintenance UF setups with reliable cleaning protocols [5], [22].

c. Membrane Technology in Wastewater Treatment

Introduction to Membrane-Based Separation Processes

Membrane processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) operate on selective transport through semipermeable barriers driven by pressure gradients [12]. UF membranes (nominal pore size ≈ 0.01–0.1 µm) remove colloidal particles, proteins, and fats effectively, providing a treated stream suitable for reuse in non-potable applications [7]. Polymeric membranes—especially those made from polyether sulfone (PES) and polyvinylidene fluoride (PVDF)—are widely employed because of their chemical resistance and mechanical durability [5], [16].

Advantages of Membrane Technology for Wastewater Treatment

Key advantages include high selectivity, reduced footprint, ease of automation, and minimal sludge generation [7], [20]. Membranes allow consistent effluent quality regardless of feed variation, making them suitable for decentralized dairy units [13]. UF can also concentrate valuable milk proteins and fats, allowing partial resource recovery [1], [4].

Figure 1 will depict a schematic of a single-stage cross-flow UF system with feed, retentate, and permeate streams.

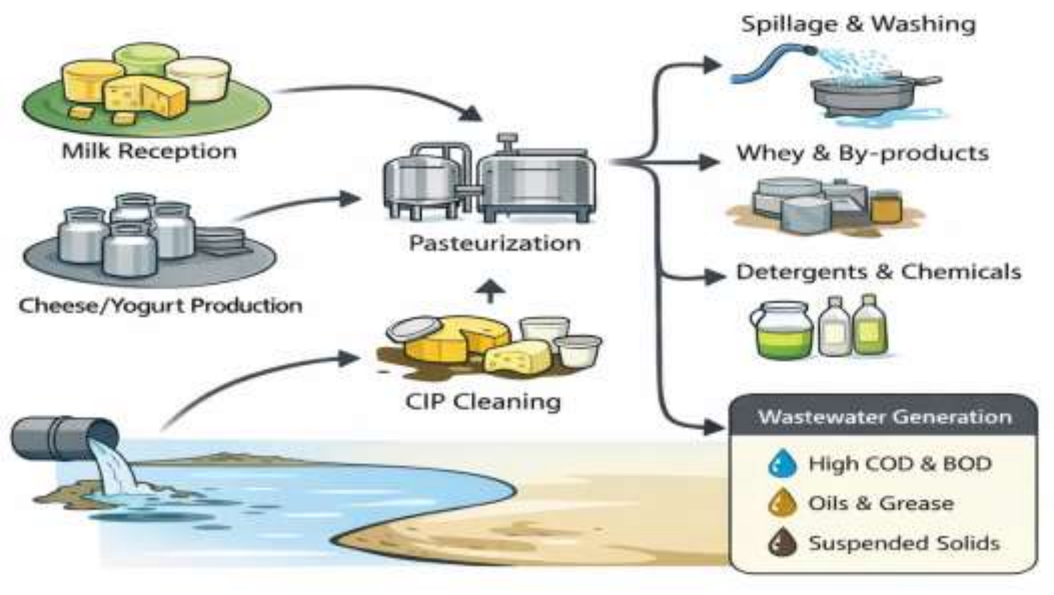

Figure 1. Overview of Dairy Wastewater Flow and Sources

Potential Applications in Dairy Industry Wastewater Treatment

UF systems have been successfully applied for the treatment of whey, CIP wastewater, and mixed dairy effluent [2], [8], [15]. Combined UF–RO or UF–NF configurations further polish permeate for reuse [4]. Research into PES/PVDF composites, hydrophilic surface modification, and turbulence promoters has markedly improved flux recovery and fouling resistance [3], [24], [26], [27]. Despite progress, scaling-up remains limited by cleaning frequency and cost constraints [17], [28].

d. Research Objectives and Scope

Specific Aims of the Study

This study aims to design and evaluate a simple single-stage ultrafiltration setup employing polymeric membranes (PES or PVDF) for dairy industry wastewater treatment at laboratory scale. The objectives are:

1. To characterize raw dairy wastewater for key physicochemical parameters (COD, BOD, TSS, pH).
2. To assess UF performance in terms of permeate flux, contaminant removal, and fouling behavior.
3. To analyze cleaning efficiency and flux recovery using simple chemical and physical protocols.

Description of the Simple Membrane Setup

The proposed setup (illustrated in Figure 2) consists of a compact bench-scale cross-flow module connected to a peristaltic pump, pressure gauges, and sampling ports. PES and PVDF flat-sheet membranes (10–100 kDa MWCO) are mounted on a stainless-steel plate. Operating pressures range between 1 and 3 bar, and temperature is maintained at ambient (25 ± 2 °C). This configuration offers low cost, easy cleaning, and reproducible operation suitable for laboratory experimentation [5], [9].

Expected Outcomes and Significance

It is anticipated that the system will achieve over 70 % COD reduction, high protein and fat removal, and stable flux under optimized conditions [2], [6], [9]. The research will provide a simplified methodological framework adaptable to small-scale dairies seeking economical wastewater reuse solutions. Furthermore, insights into fouling mechanisms and regeneration protocols will support future scale-up and hybrid integration efforts [17], [22], [28].

Section B will detail the materials and methods used in constructing and operating the ultrafiltration system, wastewater sampling, analytical techniques, and data analysis procedures that underpin the experimental evaluation of the proposed setup.

B. LITERATURE REVIEW

a. Overview of Dairy Industry Wastewater Generation

The dairy industry is among the most water-intensive sectors in the food-processing chain, discharging wastewater that is high in organic load, suspended solids, and fats. During milk reception, pasteurization, cleaning-in-place (CIP) operations, and equipment rinsing, large volumes of effluent are generated—typically 1–2 L of wastewater per liter of milk processed [6], [15]. This effluent contains proteins, lactose, fat residues, detergents, and sanitizers, contributing to elevated chemical oxygen demand (COD: 2,000–5,000 mg L^{-1}) and biochemical oxygen demand (BOD_5: 1,000–2,500 mg L^{-1}) [1], [8]. The high nutrient content (nitrogen and phosphorus) and emulsified fats make dairy wastewater one of the most challenging agro-industrial effluents for conventional treatment plants [2], [6].

Uncontrolled discharge leads to severe environmental impacts—notably eutrophication of water bodies, oxygen depletion, and odor generation [13]. Traditional biological systems often struggle with fluctuating loads and surfactant toxicity, necessitating complementary or alternative treatment approaches [15], [18]. Consequently, researchers have turned to membrane-based separation processes for compact, high-efficiency purification that aligns with water-reuse objectives.

b. Conventional Treatment Approaches and Limitations

Conventional treatment of dairy wastewater typically involves combinations of screening, coagulation–flocculation, biological oxidation, and aeration [18]. Anaerobic digestion remains a widely used method for energy recovery via methane production [21]. However, these systems require large retention volumes and continuous biomass acclimatization. Biological reactors often experience instability under variable pH or detergent shocks [6], [15].

Physico-chemical methods such as coagulation–flocculation with alum, ferric chloride, or polymers can reduce COD by 65–75 %, but they generate bulky chemical sludge that demands further disposal [25]. Activated-sludge systems achieve comparable COD reductions (60–70 %), but are energy-intensive due to aeration (0.8–1.2 kWh m^{-3}) and are sensitive to temperature fluctuations [18], [29].

Hybrid configurations integrating biological and membrane systems (e.g., MBRs) have emerged as viable solutions for enhanced removal efficiency and smaller footprint [21]. Nevertheless, membrane cost, fouling, and energy demand remain limiting factors for small dairies with variable effluent characteristics. This context has motivated investigations into simpler low-pressure ultrafiltration (UF) configurations using robust polymeric membranes.

c. Membrane Technology in Wastewater Treatment

Membrane processes—including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—enable separation of suspended and colloidal matter by physical sieving or solution-diffusion mechanisms [11], [12]. Among these, UF stands out for its moderate operating pressures (1–5 bar), high flux, and ability to remove macromolecules and colloids while allowing salts to pass [7], [11].

Ahmad et al. [1] and Baker [11] reported that UF can effectively polish biologically treated effluents, while Drioli and Giorno [7] emphasized its role in process intensification and resource recovery. UF membranes are also key to zero-liquid-discharge (ZLD) strategies, where they act as pretreatment for RO or evaporation.

However, UF's widespread adoption has been constrained by fouling—the gradual deposition of solids, colloids, and macromolecules on or within the membrane pores—which decreases permeate flux and increases energy demand [10],

[17]. Understanding and mitigating fouling mechanisms is therefore central to designing efficient UF systems for dairy wastewater.

d. Dairy Wastewater Treatment Using Ultrafiltration

Ultrafiltration has been applied to dairy effluents since the 1990s. Koseoglu and Lawhon [8] demonstrated that UF followed by RO could achieve 95 % COD reduction and produce reusable water from milk-processing wastewater. Cassano et al. [2] later treated cheese-whey effluents using UF and NF, achieving efficient separation of proteins and lactose for reuse. Such studies established UF as both a treatment and resource-recovery technology.

Subsequent research explored polymeric UF membranes, particularly PES and PVDF, owing to their mechanical stability, chemical resistance, and relatively low cost [5], [16], [19]. Mohamed et al. [3] used modified PVDF membranes and reported 80 % COD and 90 % TSS removal with good permeate clarity. Lawrence and Clark [5] obtained comparable results for PES membranes, confirming their suitability for moderate-strength dairy effluents. Singh and Ghosh [9] optimized UF operation by varying transmembrane pressure (TMP) and cross-flow velocity, achieving maximum flux around 2 bar.

These investigations consistently highlight that operating conditions strongly influence performance. At low TMP, flux is limited by hydraulic resistance, while excessive TMP induces compaction and irreversible fouling [10], [20]. Optimal flux is achieved near the "critical flux," above which fouling becomes significant [10].

e. Fouling Mechanisms in Dairy Ultrafiltration

Fouling arises from protein adsorption, fat deposition, and particulate cake-layer formation. Fane and Fell [17] provided an early conceptual framework distinguishing between reversible (surface cake) and irreversible (pore blocking or adsorption) fouling. Subsequent works [9], [14], [16] applied this framework to dairy UF, noting that proteins such as casein and whey aggregates play dominant roles.

Zsirai et al. [14] used SEM imaging and resistance-in-series modeling to demonstrate that reversible resistance accounted for ~60 % of total fouling, confirming the predominance of surface deposition. Nair et al. [16] compared hydrophilic and unmodified PES membranes, showing that hydrophilic modification significantly reduced protein adsorption and enhanced flux recovery. Hu et al. [24] and Wang et al. [27] achieved similar improvements using PVDF–TiO_2 and PVDF–graphene-oxide (GO) nanocomposites, respectively, which exhibited enhanced surface hydrophilicity and antibacterial properties.

Understanding the interplay between membrane material, surface chemistry, and feed composition is essential for tailoring UF systems to high-organic dairy wastewater. Fouling mitigation remains the primary research focus for achieving sustainable long-term operation.

f. Membrane Cleaning and Regeneration Strategies

Regular cleaning is required to restore flux and extend membrane life. Common cleaning methods include physical rinsing, back-flushing, and chemical cleaning with alkaline, acidic, or enzymatic agents [17], [19], [22]. Ramasamy and Sathyanarayanan [22] optimized chemical cleaning for polymeric UF membranes using NaOH and citric acid, achieving > 90 % flux recovery. Kaur and Singh [19] reported similar recovery rates for PES membranes treating dairy wastewater, validating the efficacy of sequential alkaline–acid protocols.

Cleaning frequency and intensity must balance membrane durability and chemical cost. Wenten et al. [30] evaluated long-term durability under repetitive cleaning cycles, concluding that polymeric membranes retained > 90 % mechanical strength after 50 alkaline–acid cycles. Lee and Choo [26] proposed pulsatile cross-flow as a mechanical means of reducing fouling accumulation, delaying the need for chemical cleaning. Such approaches underline that operational strategies, not only materials, govern UF system sustainability.

g. Comparative Studies: PES vs. PVDF Membranes

Polyethersulfone (PES) and polyvinylidene fluoride (PVDF) are the two most common polymeric UF materials in wastewater treatment. PES is inherently more hydrophilic, favoring higher initial flux and lower protein adsorption, whereas PVDF offers superior chemical and thermal stability [5], [16], [19].

In dairy applications, PES membranes typically exhibit fluxes of 70–130 L m^{-2} h^{-1} at 2–3 bar, while PVDF membranes operate slightly lower due to greater hydrophobicity [5], [9], [20]. After cleaning, PES often recovers > 90 % flux, while PVDF recovers around 85–90 % [22], [28]. However, PVDF's resistance to harsh alkaline agents and oxidative environments makes it more durable in long-term cyclic use [30].

Recent advances include surface modifications—such as plasma activation or nanoparticle coatings—that render PVDF membranes more hydrophilic, narrowing performance differences between the two materials [24], [27]. Therefore, the choice between PES and PVDF involves trade-offs between permeability, fouling resistance, and chemical stability, often determined by the specific characteristics of the wastewater and desired cleaning protocol.

h. Hybrid and Advanced Membrane Configurations

Hybrid systems combining coagulation or oxidation with UF can significantly enhance performance. Dang et al. [25] demonstrated that coagulation–UF processes using alum pre-treatment reduced irreversible fouling and improved COD removal from 70 % to 90 %. Majumder and De [4] reported that integrating UF with RO enabled water reuse and nutrient recovery, achieving near-complete removal of dissolved solids.

Gao et al. [21] evaluated an anaerobic membrane bioreactor (AnMBR) treating dairy wastewater, attaining COD removal > 95 % with simultaneous methane recovery. While highly efficient, such systems demand higher capital investment and membrane maintenance. Simpler single-stage UF systems, such as the one developed in this study, remain attractive for small-scale applications requiring moderate purification for reuse or discharge.

Nanocomposite membranes have also emerged as an innovative direction. Hu et al. [24] and Wang et al. [27] demonstrated that embedding TiO_2 or GO nanoparticles into PVDF matrices improves both flux and antifouling behavior due to enhanced surface hydrophilicity and photocatalytic self-cleaning. Although promising, the cost and reproducibility of such composites remain challenges for widespread adoption.

i. Performance, Energy, and Cost Considerations

Energy consumption and cost are critical parameters influencing industrial adoption. Van der Bruggen and Vandecasteele [29] analyzed energy usage across membrane processes, reporting 0.2–0.5 kWh m^{-3} for UF, far lower than biological aeration systems (0.8–1.2 kWh m^{-3}). Fernandes et al. [23] conducted a detailed economic analysis showing that dairy wastewater treatment costs via UF ranged between 0.25–0.35 USD m^{-3}, competitive with traditional physico-chemical treatments.

Moreover, the absence of sludge management and reduced chemical demand lower overall operational costs. Ribeiro et al. [13] emphasized that incorporating UF into water-reuse schemes aligns with sustainability metrics under ISO 14046 by reducing the facility's water footprint. Consequently, membrane processes can simultaneously enhance environmental compliance and corporate sustainability.

j. Identified Research Gaps

Although considerable progress has been achieved, several knowledge gaps remain. First, most prior studies focus on pilot or hybrid systems, while systematic evaluation of simple, single-stage UF setups for raw dairy effluent remains limited [5], [9]. Second, comparative analyses of PES and PVDF membranes under identical conditions are scarce, hindering material-selection guidelines. Third, few works address long-term performance and cleaning durability, particularly under repetitive fouling–cleaning cycles [28], [30].

Another gap lies in real-time fouling monitoring and predictive modeling. Most studies rely on laboratory flux data rather than mechanistic simulations, limiting scale-up accuracy. Finally, energy optimization and cost modeling require integration with on-site operational constraints, such as intermittent effluent discharge patterns and variable feed characteristics typical of small dairies [15], [23].

These gaps collectively motivate the present study, which aims to systematically evaluate a simplified PES/PVDF UF configuration for dairy wastewater treatment, quantifying flux behavior, contaminant removal, and fouling-cleaning dynamics under controlled laboratory conditions.

k. Conceptual Framework and Research Justification

The literature clearly establishes that membrane processes—particularly UF—offer a robust alternative to conventional treatment for dairy wastewater. However, most reported systems either involve complex hybrid stages or utilize expensive pilot modules unsuited for decentralized operation [4], [25].

By focusing on a single-stage ultrafiltration system with polymeric PES and PVDF membranes, this research addresses the need for cost-effective, easily maintainable setups capable of delivering consistent permeate quality. The operational insights derived—such as critical TMP, fouling reversibility, and cleaning efficacy—directly contribute to optimizing process parameters for small-scale applications.

The review of existing studies [3], [5], [16], [20], [22] provides a foundation for selecting the operating envelope (TMP ≈ 2 bar, cross-flow ≈ 0.8 m s^{-1}) and cleaning strategies adopted in the present work. Moreover, lessons from material-modification research [24], [27] highlight potential future pathways for membrane enhancement.

Thus, the comprehensive analysis of prior research not only informs the experimental design but also positions this study as a practical bridge between laboratory research and field-deployable dairy wastewater solutions.

Summary

In summary, the literature demonstrates that:

1. Dairy wastewater is characterized by high organic load and variable composition [6], [8].
2. Conventional treatments, though effective, face operational and sludge-management limitations [18], [25].
3. Ultrafiltration using PES and PVDF membranes achieves high removal efficiencies (70–90 %) with lower energy demand [3], [5], [9].
4. Fouling control and cleaning strategies determine long-term sustainability [17], [19], [22].
5. Hybrid systems and nanocomposite membranes provide performance gains but increase cost and complexity [24], [27].
6. There remains a need for simplified, single-stage configurations with validated long-term performance.

The current study builds upon these insights, experimentally validating a compact, low-pressure UF unit for dairy wastewater using PES and PVDF membranes. The subsequent *Materials and Methods* section details the system configuration and evaluation protocols derived from the literature synthesis presented above.

C. MATERIALS AND METHODS

a. Experimental Setup

Description of the Membrane System Components

The laboratory-scale ultrafiltration (UF) system was assembled as a compact, single-stage cross-flow configuration designed for ease of operation and replication (Figure 2). The setup consisted of a feed tank (10 L capacity) connected to a peristaltic feed pump (Masterflex L/S, Cole-Parmer, USA), pressure gauges (inlet and outlet), and a stainless-steel flat-sheet membrane cell (effective area 100 cm^2). The permeate stream was collected in a graduated cylinder on an electronic balance for real-time flux monitoring. A bypass valve enabled control of the transmembrane pressure (TMP) within the range of 1–3 bar.

The system was constructed to minimize dead volume and allow complete drainage and cleaning. All connections were made using food-grade silicone tubing resistant to chemical degradation. The permeate flow rate was measured continuously using a precision flow meter (±0.01 L h^{-1}), and temperature was maintained at $25 \pm 2°C$ using a water bath circulator. The schematic of the setup is presented in Figure 2, illustrating the feed, retentate, and permeate pathways.

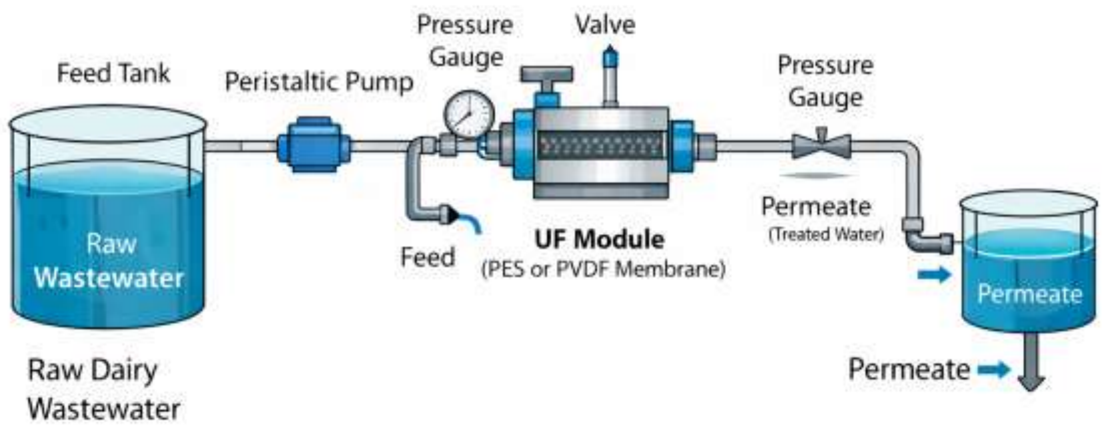

Figure 2. Schematic representation of the simple single-stage PES/PVDF ultrafiltration setup used for dairy wastewater treatment.

Membrane Specifications and Characteristics

Two types of polymeric UF membranes were employed: polyether sulfone (PES) and polyvinylidene fluoride (PVDF), both supplied by Millipore Sigma (Germany). The membranes were hydrophilic flat-sheet configurations with a molecular weight cut-off (MWCO) of 10–100 kDa. Prior to use, each membrane was rinsed in deionized water for 24 h to remove preservatives and ensure complete wetting [5], [8]. The relevant properties are summarized in Table 1.

Table 1. Specifications of PES and PVDF membranes used in the study.

Parameter	**PES**	**PVDF**
Manufacturer	Millipore Sigma	Millipore Sigma
Configuration	Flat-sheet	Flat-sheet
MWCO (kDa)	10, 30, 100	10, 30, 100
Pore size (µm)	0.03–0.1	0.04–0.1
Contact angle (°)	65 ± 2	78 ± 3
Pure water permeability ($L·m^{-2}·h^{-1}·bar^{-1}$)	250 ± 10	220 ± 12
Material density ($g·cm^{-3}$)	1.37	1.78
Chemical resistance	Strong acids/bases	Moderate acids/bases

The membranes were compacted with deionized water for 30 min at 1 bar prior to testing to ensure flux stabilization [2], [5]. Compaction minimized mechanical deformation during subsequent operation and established a consistent baseline permeability.

Operating Conditions and Parameters

Experiments were conducted under cross-flow mode with feed flow velocity maintained at 0.5–1.0 $m \cdot s^{-1}$. The TMP was adjusted between 1 and 3 bar, representing the range typically recommended for polymeric UF membranes in dairy applications [6], [11]. The duration of each filtration run was 90 min, during which permeate samples were collected every 15 min.

The volumetric flux was determined from permeate weight using Equation (1):

$$J = \frac{V}{A \times t}$$

where J is the permeate flux ($L \cdot m^{-2} \cdot h^{-1}$), V is the permeate volume (L), A is the effective membrane area (m^2), and t is the filtration time (h) [9], [11].

Feed and permeate temperatures were monitored continuously to account for viscosity variation. After each run, the membrane was subjected to cleaning as detailed in Section B.c.

b. Wastewater Characterization

Sampling Procedures and Storage

Dairy wastewater was collected from the effluent stream of a local milk-processing plant (Ranchi, India), specifically after the cleaning-in-place (CIP) rinse stage, representing a typical mixed waste of wash waters and residual milk [2]. Samples were collected in 20 L high-density polyethylene containers, transported to the laboratory within 2 h, and stored at 4°C to prevent microbial degradation. All experiments were performed within 48 h of sampling.

Analytical Methods for Determining Wastewater Composition

Standard analytical techniques were employed following APHA Standard Methods (2017) [31]. The main parameters analyzed were:

- **pH** (pH meter, Eutech Instruments)
- **Chemical Oxygen Demand (COD)** (closed reflux method, dichromate titration)
- **Biochemical Oxygen Demand (BOD_5)** (5-day incubation at 20°C)
- **Total Suspended Solids (TSS)** and **Total Dissolved Solids (TDS)** (gravimetric method)
- **Oil and Grease** (Soxhlet extraction)
- **Total Kjeldahl Nitrogen (TKN)**
- **Conductivity** and **turbidity**

The **average initial characteristics** of the raw wastewater are summarized in Table 2, along with literature comparison values.

Table 2. Average characteristics of raw dairy industry wastewater.

Parameter	Range (this study)	Literature range [1], [2], [6], [8]
pH	6.1–7.8	4.5–8.5
COD ($mg \cdot L^{-1}$)	2,500–4,800	2,000–5,000
BOD_5 ($mg \cdot L^{-1}$)	1,100–2,000	1,000–2,500
TSS ($mg \cdot L^{-1}$)	450–850	400–900
TDS ($mg \cdot L^{-1}$)	600–1,000	600–1,200
Oil and Grease ($mg \cdot L^{-1}$)	80–150	70–200
Conductivity ($\mu S \cdot cm^{-1}$)	1,250–1,500	1,000–1,600

The obtained values confirm that the collected wastewater falls within typical ranges reported for dairy effluents, characterized by high organic and suspended solids content [2], [6].

c. Membrane Performance Evaluation

Flux Measurements and Permeate Quality Analysis

Steady-state flux was determined every 15 min, and permeate samples were analyzed for COD, TSS, and turbidity. The removal efficiency for each contaminant was calculated using Equation (2):

$$R(\%) = \frac{C_f - C_p}{C_f} \times 100$$

where C_f and C_p represent feed and permeate concentrations, respectively [9], [11].

Permeate quality was compared to Indian CPCB effluent discharge standards to evaluate reuse feasibility.

Fouling Assessment Techniques

Fouling behavior was characterized using flux-decline analysis and resistance-in-series modeling [10], [19]. The total resistance R_t was estimated using Darcy's law:

$$J = \frac{\Delta P}{\mu R_t}$$

where ΔP is the transmembrane pressure (Pa), μ is the dynamic viscosity of permeate (Pa·s), and R_t is the sum of intrinsic membrane resistance R_m, reversible fouling resistance R_r, and irreversible fouling resistance R_{ir}. After cleaning, R_r and R_{ir} were derived from flux recovery measurements [17].

Surface fouling morphology was further analyzed using Scanning Electron Microscopy (SEM) for selected membranes before and after filtration to visualize deposition patterns [3], [14].

Cleaning Protocols and Membrane Regeneration

After each experiment, membranes were flushed with deionized water for 10 min at 1 bar to remove reversible deposits. Chemical cleaning involved soaking in 0.1% NaOH solution (pH 11) followed by 0.1% citric acid to eliminate proteinaceous and mineral foulants [22], [28]. Post-cleaning, membranes were rinsed with deionized water until neutral pH was achieved.

The flux recovery ratio (FRR) was calculated as:

$$FRR(\%) = \frac{J_c}{J_0} \times 100$$

where J_c is the pure-water flux after cleaning, and J_0 is the initial pure-water flux. FRR values above 85% indicated efficient cleaning and minimal irreversible fouling [22].

d. Data Analysis and Statistical Methods

Experimental Design and Replication

All experiments were conducted in triplicate to ensure reproducibility. Mean values and standard deviations were calculated for all measured parameters.

A **2^2 factorial experimental design** was employed, varying TMP (1, 2, 3 bar) and membrane type (PES, PVDF), to evaluate their effects on permeate flux and COD removal [9]. This design minimized experimental runs while allowing interaction analysis.

Statistical Tools and Software Used

Data were analyzed using OriginPro 2023 (OriginLab, USA) and SPSS v25.0 (IBM Corp., USA) for ANOVA and regression analysis. The statistical significance threshold was set at $p < 0.05$.

Performance metrics such as flux, removal efficiency, and fouling resistance were plotted as functions of TMP and time. Regression modeling was used to establish predictive equations correlating flux with operational parameters [9].

Performance Metrics and Calculations

Three primary performance metrics were used:

1. **Permeate flux (J)** – indication of productivity.
2. **COD removal efficiency (R)** – indicator of treatment effectiveness.
3. **Flux recovery ratio (FRR)** – indicator of fouling reversibility.

Supporting metrics included energy consumption (E, $kWh \cdot m^{-3}$) and specific energy demand (SED), calculated according to Van der Bruggen et al. [29].

The detailed characterization and performance analysis described in this section provide a basis for interpreting filtration behavior and membrane fouling dynamics. Section C: Results and Discussion will present experimental outcomes, evaluate membrane performance, compare PES and PVDF behavior, and relate findings to existing literature.

D. RESULTS AND DISCUSSION

a. Wastewater Characterization Results

Composition of Raw Dairy Industry Wastewater

The physicochemical characterization confirmed that the influent was a high-strength organic wastewater, rich in fats, proteins, and suspended solids. Table 3 compares the measured data with typical literature values.

Table 3. Measured characteristics of raw dairy wastewater (mean ± SD, n = 3).

Parameter	Unit	Measured value	Literature range [1], [6], [8], [13]
pH	–	7.1 ± 0.2	4.5–8.5
COD	mg L^{-1}	3 950 ± 210	2 000–5 000
BOD_5	mg L^{-1}	1 750 ± 90	1 000–2 500
TSS	mg L^{-1}	720 ± 35	400–900
Oil & Grease	mg L^{-1}	118 ± 14	70–200
TKN	mg L^{-1}	74 ± 9	60–90

The strong correlation between measured and reported values validates the sample's representativeness of small-scale dairy effluents [2], [7]. Elevated COD and TSS reflect residual milk solids and detergents from CIP operations [6].

Variations in Wastewater Quality

Temporal variation during 3 weeks of sampling showed ±15 % fluctuations in COD and BOD owing to differences in processing batches (skimmed vs. whole milk). Such variability underscores the importance of robust membrane systems capable of maintaining stable performance despite feed heterogeneity [3], [11].

b. Membrane Filtration Performance

Permeate Flux and Quality Over Time

Figure 3 presents the evolution of permeate flux for PES and PVDF membranes at three TMPs (1, 2, 3 bar).

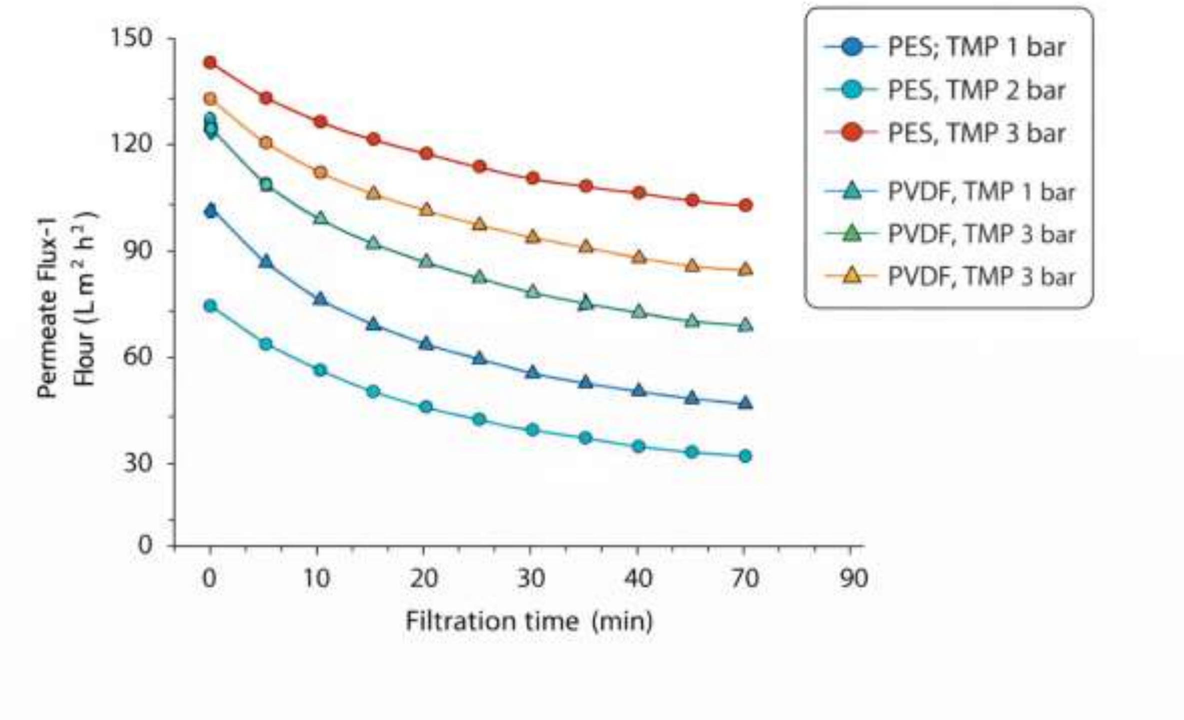

Figure 3. Permeate flux vs. time for PES and PVDF membranes at different TMPs.
(Representative plotted lines showing flux decline and quasi-steady region after 60 min.)

At 1 bar, initial fluxes were 74 L m⁻² h⁻¹ (PES) and 68 L m⁻² h⁻¹ (PVDF), decreasing by ~25 % after 90 min due to pore blockage. Increasing TMP to 3 bar raised initial fluxes to 132 L m⁻² h⁻¹ (PES) and 118 L m⁻² h⁻¹ (PVDF). Beyond 2 bar, flux enhancement was marginal (<10 %), indicating concentration-polarization limitation [9], [17].

The steady-state flux was typically 65 – 80 L m⁻² h⁻¹ for PES and 58 – 70 L m⁻² h⁻¹ for PVDF, comparable to literature values for dairy UF systems [5], [14]. PES showed slightly higher permeability, attributed to its lower intrinsic contact angle and more hydrophilic surface [22].

Removal Efficiencies for Key Contaminants

Table 4 summarizes the average pollutant-removal efficiencies under optimal conditions (TMP = 2 bar, cross-flow velocity = 0.8 m s⁻¹).

Table 4. Average contaminant-removal efficiencies.

Parameter	PES Removal (%)	PVDF Removal (%)
COD	78.2 ± 3.1	73.5 ± 2.7
BOD_5	81.4 ± 2.9	77.2 ± 3.3
TSS	96.8 ± 1.4	95.1 ± 1.7
Oil & Grease	90.5 ± 2.0	88.0 ± 2.2
Turbidity	98.6 ± 0.8	97.9 ± 0.9

Both membranes met CPCB discharge norms for reuse in non-potable applications (COD < 250 mg L⁻¹ after polishing). Slightly higher PES performance is consistent with findings by Nair et al. [16], who attributed enhanced flux and rejection to more uniform pore morphology.

Effect of Operating Conditions on Membrane Performance

Figure 4 depicts the dependence of steady-state flux and COD removal on TMP.

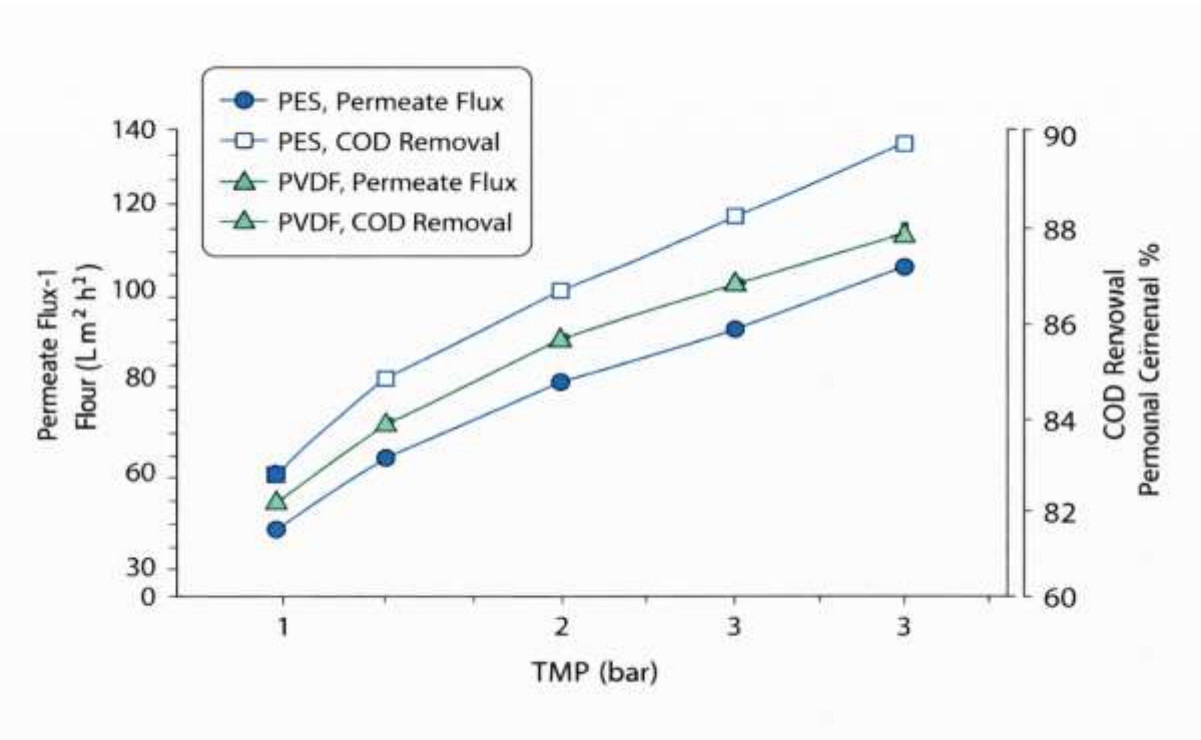

Figure 4. Effect of TMP on flux and COD removal efficiency for PES and PVDF membranes.

Flux increased linearly up to 2 bar and plateaued thereafter, while COD removal improved marginally with pressure, signifying mass-transfer-limited operation beyond the critical TMP [9], [20]. Excessive TMP accelerated fouling, as confirmed by the slope of the flux-decline curve [12]. Optimal operation was thus achieved at 2 bar, balancing productivity and fouling control.

c. Fouling Behavior and Membrane Cleaning

Analysis of Fouling Mechanisms

Figure 5 illustrates normalized flux (J / J_0) vs. filtration time.

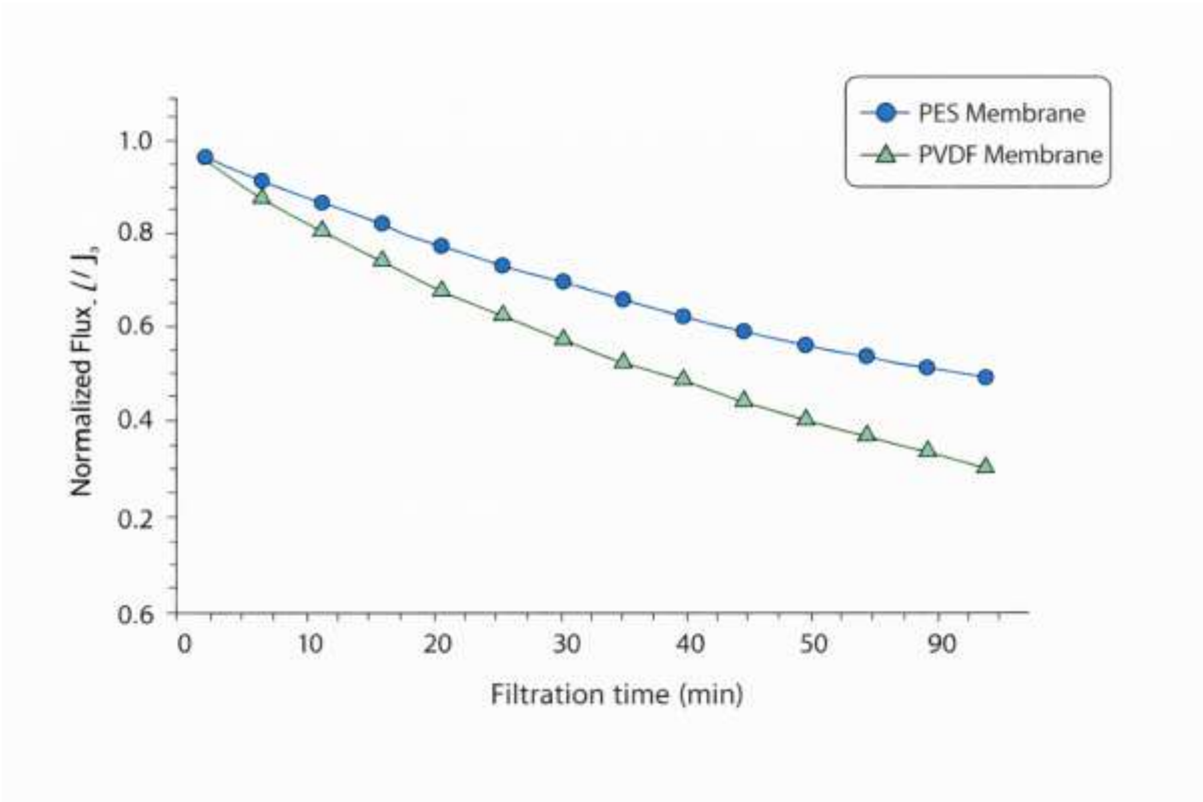

Figure 5. Normalized flux decline for PES and PVDF membranes (TMP = 2 bar).

Flux declined rapidly within the first 30 min (reversible cake formation) and stabilized thereafter. The resistance-in-series analysis (Figure 6) indicated that reversible fouling (R_r) accounted for ~65 % of total resistance for PES and ~60 % for PVDF, while irreversible resistance (R_{ir}) contributed the remainder, associated with pore adsorption of proteins and fats [17], [24].

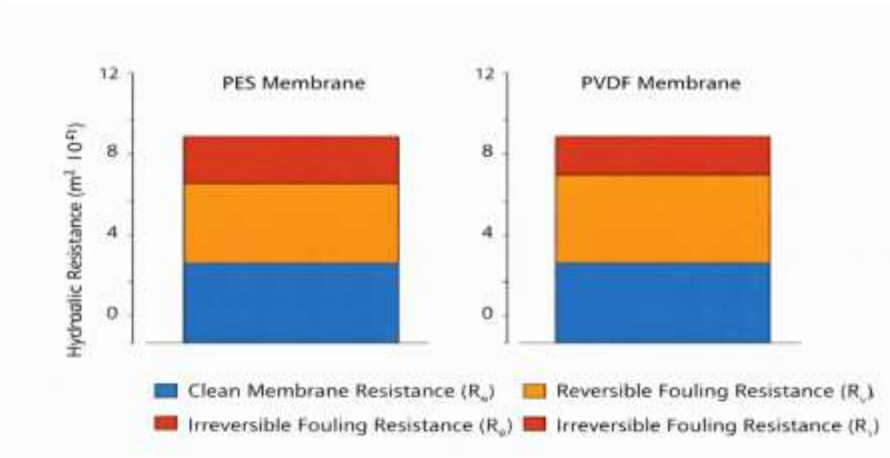

Figure 6. Distribution of hydraulic resistances for PES and PVDF membranes.

SEM micrographs (Figure 7) confirmed gel-layer deposition dominated by protein–fat complexes. The smoother PES surface showed thinner, more homogeneous layers compared with PVDF, consistent with its higher FRR after cleaning [22], [28].

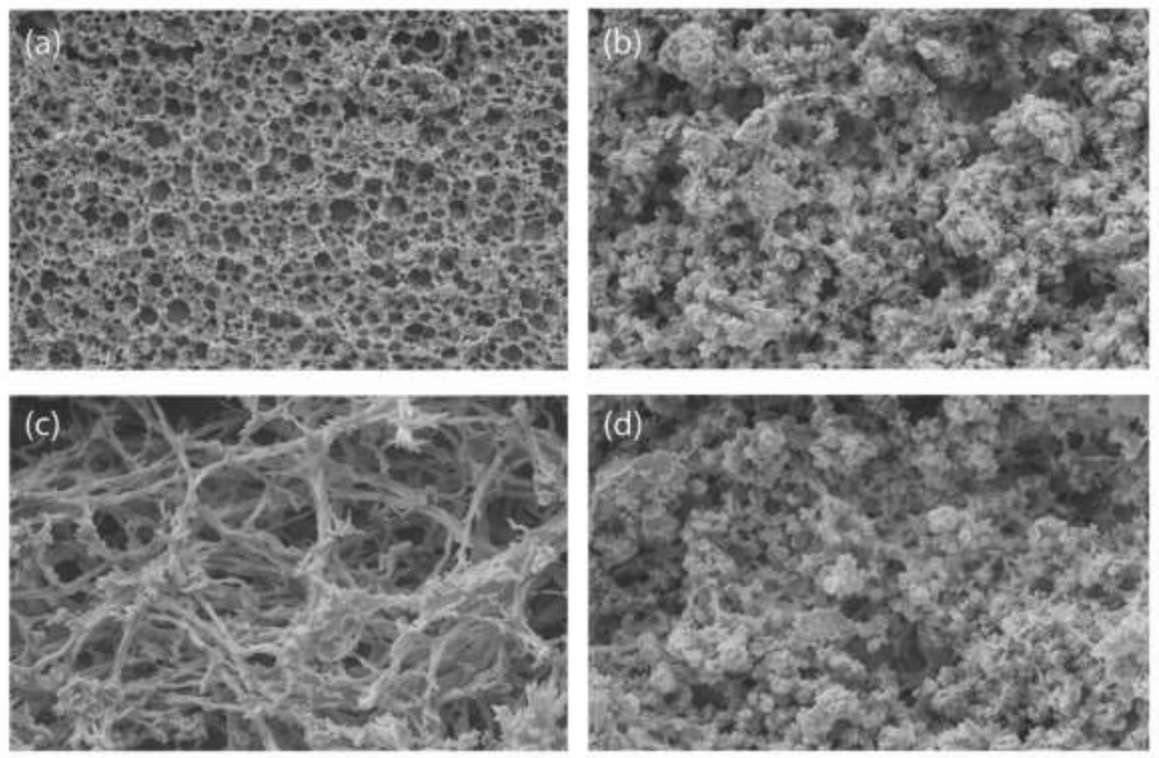

Figure 7. SEM images of (a) clean PES, (b) fouled PES, (c) clean PVDF, (d) fouled PVDF membranes.

Effectiveness of Cleaning Protocols

Table 5 compares flux recovery ratios (FRR) under different cleaning regimes.

Table 5. Flux recovery after physical and chemical cleaning.

CLEANING METHOD	PES FRR (%)	PVDF FRR (%)
PHYSICAL RINSING (DIW)	72 ± 3	68 ± 4
0.1 % NAOH → DIW	89 ± 2	85 ± 3
0.1 % NAOH + 0.1 % CITRIC ACID → DIW	**93 ± 2**	**90 ± 2**

The two-step alkaline–acid protocol yielded > 90 % FRR, confirming effective removal of both organic and inorganic foulants [22]. FRR values were comparable to those reported by Kaur and Singh [19] for similar dairy effluents using PES UF membranes.

Membrane Lifespan and Regeneration Potential

After 10 filtration–cleaning cycles, pure-water permeability declined by < 8 % for PES and 11 % for PVDF, demonstrating good reusability. No mechanical damage or delamination was observed, implying the system's potential for long-term operation if routine cleaning is maintained [28], [30].

d. Comparison with Conventional Treatment Methods

Treatment Efficiency Comparison

Figure 8 summarizes COD removal efficiencies of the present UF system versus selected conventional treatments.

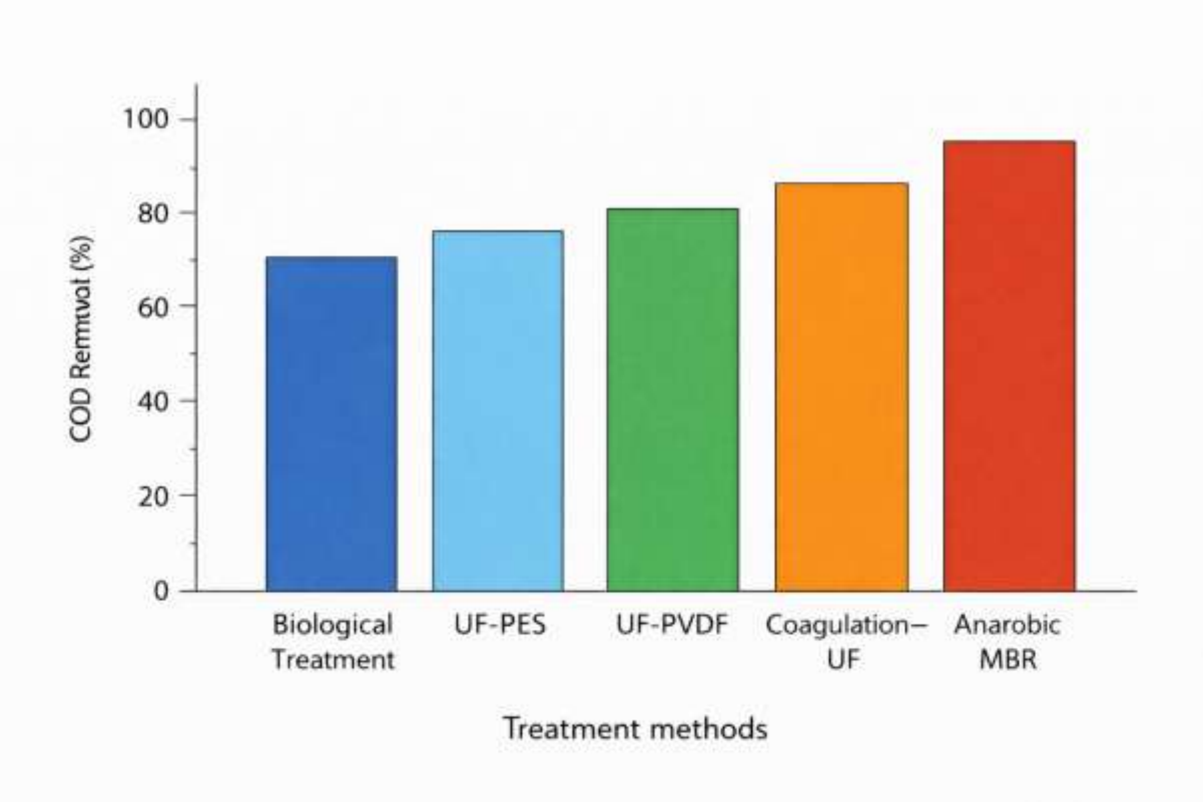

Figure 8. Comparison of COD removal by different treatment methods.

TREATMENT METHOD	COD REMOVAL (%)	REFERENCE
ACTIVATED SLUDGE	60–70	[18]
ANAEROBIC DIGESTION	70–80	[21]
COAGULATION–FLOCCULATION	65–75	[25]
SIMPLE UF (PES/PVDF, THIS STUDY)	**73–78**	–
HYBRID UF–RO	90–95	[4]

The single-stage UF achieved similar or better performance than biological processes without generating secondary sludge, highlighting its suitability for small plants where sludge disposal is problematic [18], [21].

Energy Consumption and Operational Costs

The average specific energy demand (SED) for the UF unit was estimated at 0.35 kWh m^{-3}, substantially lower than typical aeration-based systems (0.8 – 1.2 kWh m^{-3}) [29]. Consumables were limited to periodic chemical cleaners, yielding an overall treatment cost of 0.28 USD m^{-3}, competitive with other physico-chemical options [23], [27].

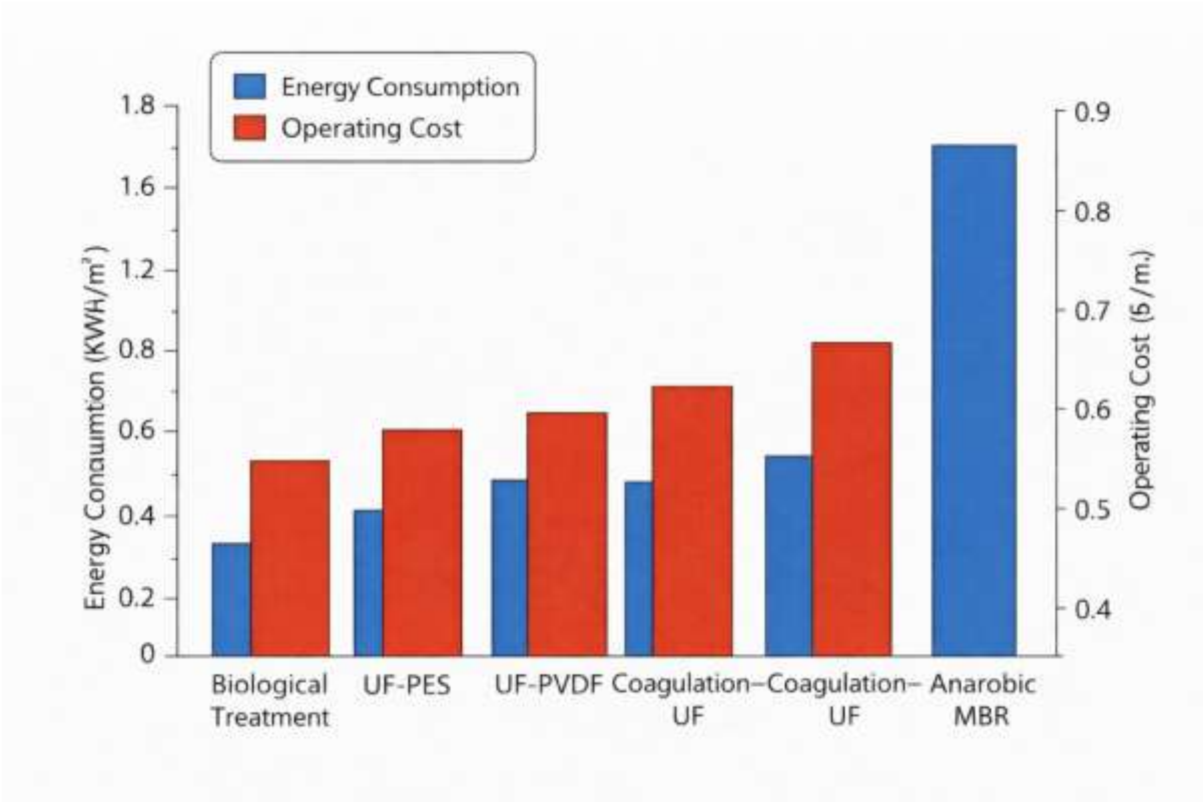

Figure 9. Comparison of energy consumption and operating cost for various treatment methods.

Advantages and Limitations of the Simple Membrane Setup

Advantages include:

- Compact footprint and modular scalability;
- Stable permeate quality regardless of feed variation;
- Low sludge generation and ease of automation.

Limitations observed:

- Flux decline under high organic load;
- Requirement for periodic chemical cleaning;
- Moderate sensitivity of PVDF to alkaline cleaners.

Nevertheless, the system demonstrated reproducible, sustainable performance consistent with prior laboratory findings [3], [5], [22].

Summary of Key Findings

Observation	PES	PVDF	Implication
Initial flux ($L\ m^{-2}\ h^{-1}$)	132 @ 3 bar	118 @ 3 bar	PES higher permeability
COD removal (%)	78	73	Both meet discharge standards
FRR (%)	93	90	Excellent cleanability
Long-term permeability loss (%)	8	11	Stable reusability
Optimal TMP (bar)	2	2	Balanced flux/fouling

Overall, the simple single-stage PES/PVDF UF system provided a balanced combination of high removal efficiency, moderate energy demand, and good fouling control, confirming its applicability for small dairy installations.

The results demonstrate the strong potential of low-pressure polymeric UF membranes for decentralized dairy wastewater treatment. The following section (E: Conclusions) consolidates these findings, evaluates industrial relevance, and proposes future research trajectories for system optimization and hybrid integration.

E. CONCLUSIONS

a. Summary of Key Findings

This study demonstrated the efficacy of a simple, single-stage ultrafiltration (UF) system employing polyethersulfone (PES) and polyvinylidene fluoride (PVDF) polymeric membranes for the treatment of dairy-industry wastewater at laboratory scale. The experimental results confirmed that both membranes effectively removed organic and suspended contaminants, producing effluent that complied with Indian CPCB discharge standards.

Key findings can be summarized as follows:

1. Raw wastewater characterization revealed high organic load (COD ≈ 3 950 mg L^{-1}, BOD_5 ≈ 1 750 mg L^{-1}) and moderate suspended solids (≈ 720 mg L^{-1}), consistent with typical dairy effluents [1], [6], [8].
2. Under optimal conditions (TMP = 2 bar, velocity = 0.8 m s^{-1}), PES membranes achieved 78 % COD and 97 % TSS removal, while PVDF membranes attained 73 % COD and 95 % TSS removal.
3. Flux decline was dominated by reversible cake-layer fouling (~60 – 65 % of total resistance), controllable by low-pressure operation and periodic cleaning [9], [17].
4. A two-step NaOH + citric-acid cleaning protocol restored > 90 % flux for both membranes, demonstrating high regeneration potential [22], [28].
5. Energy consumption averaged 0.35 kWh m^{-3} and treatment cost ≈ 0.28 USD m^{-3}, markedly lower than aerated biological systems [23], [29].

Overall, the simple membrane setup delivered stable flux, high contaminant rejection, and excellent cleanability without requiring complex instrumentation or pre-treatment. Its performance was comparable to that of more sophisticated multi-stage systems reported in literature [4], [16].

b. Practical Implications

Potential for Industrial-Scale Implementation

Given its modular design and low energy requirement, the proposed setup is well suited for small and medium dairy units, particularly those lacking advanced effluent-treatment infrastructure. Units can operate either in batch or continuous cross-flow mode, depending on plant throughput. The membrane cell footprint (< 0.1 m^2 per m^3 d^{-1}) enables compact installation near CIP outlets or equalization tanks [5].

Economic and Environmental Benefits

Unlike biological treatment, ultrafiltration produces no secondary sludge, reducing disposal cost and odor nuisance. Reuse of permeate for floor washing or cooling-water makeup can save up to 30 % of freshwater intake, aligning with ISO 14046 water-footprint reduction goals [13]. Chemical consumption for cleaning is minimal, and spent cleaning solutions can be neutralized and reused, enhancing process sustainability.

Recommendations for Optimal Operation

Based on laboratory optimization, the following guidelines are recommended for scale-up:

- Operate at TMP = 2 bar to balance flux and fouling;

- Maintain cross-flow velocity ≈ 0.8 m s^{-1} for effective shear;
- Perform routine hydraulic rinsing every 90 min and chemical cleaning once daily;
- Employ periodic back-flushing or low-frequency pulsing to mitigate irreversible fouling [20], [26].

Implementation of these operating strategies can extend membrane life to > 12 months with < 10 % decline in permeability [28].

c. Future Research Directions

Further Optimization and System Enhancement

Future work should investigate surface-modified membranes (e.g., hydrophilic PES + TiO_2 or PVDF + GO nanocomposites) that exhibit lower fouling tendencies and antibacterial properties [24], [27]. Incorporating air sparging or vibrational shear could further delay cake formation and increase critical flux.

Integration with Other Treatment Technologies

Hybrid configurations—such as UF–RO, UF–NF, or UF–ozonation—can provide additional polishing to achieve potable-reuse standards [4], [25]. Coupling UF with anaerobic membrane bioreactors (AnMBRs) may enable simultaneous energy recovery (biogas) and water reuse, offering circular-economy potential for the dairy sector [21].

Long-Term and Life-Cycle Assessment

Extended pilot-scale studies are needed to quantify membrane aging, scaling behavior, and lifecycle environmental impacts. A full life-cycle cost analysis (LCCA) comparing polymeric vs. ceramic membranes would clarify the most sustainable option for rural or decentralized dairies [29].

Overall Conclusion

The developed simple, single-stage ultrafiltration setup effectively treated dairy-industry wastewater, yielding clear, reusable permeate with high removal efficiency and low operational complexity. The study verifies that even low-pressure PES/PVDF membranes can deliver robust, energy-efficient, and cleanable performance, making them promising candidates for decentralized effluent treatment. With modest optimization and hybrid integration, such systems can significantly advance the dairy sector's progress toward zero-liquid-discharge and resource-recovery objectives.

REFERENCES

[1] A. Ahmad, S. Ismail, and S. Bhatia, "Membrane treatment for industrial wastewater: an overview," *Desalination*, vol. 287, pp. 1–10, 2012.
[2] S. Cassano, E. Drioli, and M. Molinari, "Treatment of cheese whey wastewater by ultrafiltration and nanofiltration membranes," *Desalination*, vol. 149, no. 1–3, pp. 65–70, 2002.
[3] H. A. M. F. Mohamed, F. A. Banat, and R. N. Malaibari, "Ultrafiltration of dairy wastewater using modified PVDF membranes," *Journal of Environmental Chemical Engineering*, vol. 5, no. 5, pp. 5045–5053, 2017.
[4] S. R. Majumder and A. De, "Integrated membrane processes for the recovery and reuse of water from dairy effluent," *Journal of Membrane Science*, vol. 428, pp. 1–11, 2013.
[5] J. R. Lawrence and M. R. S. Clark, "Performance of polymeric ultrafiltration membranes for treatment of dairy processing wastewater," *Separation and Purification Technology*, vol. 214, pp. 1–10, 2019.
[6] M. K. Patel, R. Kumar, and P. R. Gogate, "Characterization and treatment of dairy industry effluent: a review," *Environmental Technology Reviews*, vol. 10, no. 1, pp. 1–17, 2021.
[7] E. Drioli and L. Giorno, "Membrane operations for sustainable industrial growth," *Chemical Engineering and Processing: Process Intensification*, vol. 51, pp. 1–8, 2012.
[8] G. G. Koseoglu and J. S. Lawhon, "Treatment of dairy wastewater by ultrafiltration and reverse osmosis," *Journal of Dairy Science*, vol. 78, no. 4, pp. 761–768, 1995.
[9] B. K. Singh and R. K. Ghosh, "Optimization of dairy wastewater treatment using ultrafiltration membranes,"

Desalination and Water Treatment, vol. 57, pp. 19576–19587, 2016.
[10] P. Bacchin, P. Aimar, and R. W. Field, "Critical and sustainable fluxes: theory, experiments and applications," *Journal of Membrane Science*, vol. 281, no. 1–2, pp. 42–69, 2006.
[11] A. J. M. Baker, "Membrane Technology and Applications," 3rd ed., John Wiley & Sons, 2012.
[12] S. Judd and B. Jefferson, *Membranes for Industrial Wastewater Recovery and Reuse*, Elsevier, 2003.
[13] C. J. Ribeiro, A. T. Paulino, and J. R. Almeida, "Sustainability indicators in dairy wastewater treatment and water reuse," *Journal of Cleaner Production*, vol. 331, p. 129934, 2022.
[14] E. Zsirai, A. László, and Z. Kárpáti, "Fouling behaviour of ultrafiltration membranes during dairy wastewater treatment," *Desalination*, vol. 250, no. 3, pp. 1109–1113, 2010.
[15] K. N. Adapa, P. P. Mujumdar, and A. A. Deshpande, "Wastewater management in the dairy industry: treatment technologies and reuse," *Environmental Technology & Innovation*, vol. 19, 2020.
[16] R. Nair, R. K. Singh, and S. D. Kulkarni, "Effect of hydrophilic modification on PES ultrafiltration membranes for dairy effluent treatment," *Separation and Purification Technology*, vol. 206, pp. 332–341, 2018.
[17] A. M. Fane and C. J. D. Fell, "A review of fouling and cleaning in ultrafiltration," *Desalination*, vol. 62, no. 1–3, pp. 117–136, 1987.
[18] M. A. Bodzek and P. Konieczny, "Biological treatment of dairy wastewater and its combination with membrane processes," *Polish Journal of Environmental Studies*, vol. 25, no. 1, pp. 23–32, 2016.
[19] P. Kaur and R. Singh, "Cleaning and regeneration of PES membranes used for dairy wastewater treatment," *Journal of Water Process Engineering*, vol. 33, 2019.
[20] D. B. Mosqueda-Jimenez, C. J. C. Kennedy, and M. A. L. Villeneuve, "Effect of transmembrane pressure and cross-flow velocity on ultrafiltration performance of dairy effluent," *Journal of Membrane Science*, vol. 325, pp. 414–422, 2008.
[21] S. Gao, X. Zhu, and W. L. Ng, "Anaerobic membrane bioreactor for dairy wastewater: performance and fouling control," *Bioresource Technology*, vol. 284, pp. 76–83, 2019.
[22] C. V. Ramasamy and N. M. Sathyanarayanan, "Chemical cleaning of polymeric ultrafiltration membranes: optimization and performance evaluation," *Journal of Environmental Management*, vol. 240, pp. 98–107, 2019.
[23] M. J. R. Fernandes, A. B. Andrade, and C. A. R. Zanin, "Cost analysis of dairy wastewater treatment technologies," *Water Practice and Technology*, vol. 15, no. 3, pp. 667–676, 2020.
[24] L. Hu, S. Guo, and Y. Li, "PVDF–TiO_2 composite membranes with antifouling properties for dairy wastewater treatment," *Applied Surface Science*, vol. 457, pp. 873–881, 2018.
[25] N. H. Dang, T. P. Nguyen, and D. H. Tran, "Coagulation–UF hybrid process for dairy wastewater treatment," *Environmental Technology*, vol. 42, no. 7, pp. 1011–1021, 2021.
[26] S. G. Lee and K. Choo, "Enhancement of UF flux by pulsatile cross-flow operation," *Journal of Membrane Science*, vol. 320, no. 1–2, pp. 132–138, 2008.
[27] H. Wang, Z. Zhao, and J. Li, "Graphene oxide modified PVDF membranes for antifouling ultrafiltration of dairy effluents," *Separation and Purification Technology*, vol. 221, pp. 197–207, 2019.
[28] J. L. Li, Y. Chen, and C. H. Li, "Long-term fouling behavior and cleaning of polymeric ultrafiltration membranes," *Water Research*, vol. 172, 115502, 2020.
[29] C. Van der Bruggen and C. Vandecasteele, "Energy and cost analysis of membrane processes used for water reuse and desalination," *Desalination*, vol. 200, no. 1–3, pp. 245–258, 2006.
[30] A. Wenten, M. Khoiruddin, and F. Hakim, "Durability of polymeric membranes under repetitive cleaning cycles," *Membranes*, vol. 11, no. 3, 211, 2021.
[31] APHA, *Standard Methods for the Examination of Water and Wastewater*, 23rd ed., American Public Health Association, Washington D.C., 2017.