International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 01 | Jan - 2026 SJIF Rating: 8.586 ISSN: 2582-3930

Experimental Study on Dairy Industry Wastewater Treatment Using Membrane Technology: Performance Evaluation and Process Optimization

Sandeep C. Dighe[1], B.V. Thorat [2], S.J. Sapte [3], A.S. Dighe[4], S.D. Sandhan[5]

[1]Sr.Lect, [2345]Students of Chemical Engineering Department of Pad. Dr. V. V. Patil inst. of Tech. & Engg.(Polytechnic, Loni

Abstract

The dairy industry is one of the most water-intensive sectors within the food manufacturing domain, producing large volumes of wastewater rich in organic matter, fats, proteins, and suspended solids. Conventional biological and physicochemical treatment systems often fail to meet increasingly stringent discharge regulations or to achieve the quality required for water reuse. Membrane technologies—microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—have emerged as viable alternatives offering compact design, modular scalability, and high effluent quality.
This paper presents an experimental investigation into the treatment performance and optimization of a pilot-scale membrane system for dairy wastewater. Simulated influent with chemical oxygen demand (COD) ranging from 2 500 to 3 800 mg L^{-1} and biochemical oxygen demand (BOD_5) between 1 100 and 1 700 mg L^{-1} was treated using an integrated MF–RO configuration. Performance metrics included flux behavior, pollutant rejection efficiency, and permeate quality, which were analyzed across a range of trans-membrane pressures and cross-flow velocities. Results demonstrated COD and BOD removal efficiencies exceeding 90 %, stable flux recovery through periodic backwashing, and permeate quality compliant with ISO 14001 discharge standards, indicating strong potential for internal process water reuse. The study contributes to advancing practical understanding of energy-efficient dairy effluent treatment using hybrid membrane systems and highlights optimization strategies for industrial scale-up.

Keywords

Dairy wastewater; membrane technology; ultrafiltration; nanofiltration; reverse osmosis; permeate flux; fouling; water reuse; process optimization.

A. INTRODUCTION

a. Background

Wastewater management in the dairy sector poses significant environmental and regulatory challenges due to the complex composition of effluents generated during cleaning, pasteurization, and product processing stages [1], [2]. Typical dairy effluent contains high concentrations of organic matter (proteins, fats, lactose), suspended solids, and nutrients such as nitrogen and phosphorus, producing high biological oxygen demand (BOD) and chemical oxygen demand (COD) values often exceeding 1 000 mg L^{-1} and 3 000 mg L^{-1}, respectively [3]. Discharge of such wastewater without adequate treatment can cause eutrophication and oxygen depletion in receiving water bodies [4].

In industrialized economies, the dairy industry accounts for roughly 2–3 % of total wastewater generation within the food sector [5]. Increasing environmental awareness and enforcement of stringent discharge standards under frameworks such as the EU Water Framework Directive and the U.S. Clean Water Act have driven a paradigm shift toward advanced treatment technologies emphasizing both pollution abatement and resource recovery [6].

Conventional treatment schemes—consisting of primary screening, equalization, dissolved-air flotation (DAF), and aerobic biological treatment—have proven effective for bulk organic load reduction but remain inadequate for removing residual dissolved solids, color, and nutrients to levels enabling water reuse [7]. Moreover, biological systems are sensitive to shock loads and temperature fluctuations, leading to inconsistent performance and sludge-management burdens [8].

Membrane-based separation technologies offer an attractive solution due to their ability to produce high-quality effluent through physical separation rather than biological conversion [9]. In dairy wastewater applications, membrane processes are categorized by pore size and separation mechanism: MF (0.1–10 µm), UF (0.01–0.1 µm), NF (1–10 nm), and RO (<1 nm) [10]. Each operates under pressure gradients and is governed by size-exclusion and charge-interaction principles that determine solute rejection efficiency [11].

Recent reviews highlight that hybrid membrane configurations—such as MF-NF or MF-RO systems—achieve near-complete turbidity and color removal, COD reduction up to 85–95 %, and nutrient removal efficiencies above 90 % [12]. Bortoluzzi *et al.* [13] demonstrated that sequential MF–RO treatment achieved 94 % TKN and 84 % TOC removal, yielding permeate suitable for Cleaning-in-Place (CIP) reuse. Similarly, Galvão [14] emphasized that water reuse via membrane treatment could reduce freshwater consumption in dairy plants by 30–40 %.

Fig. 1 illustrates the schematic flow of dairy wastewater generation and potential membrane treatment integration points.

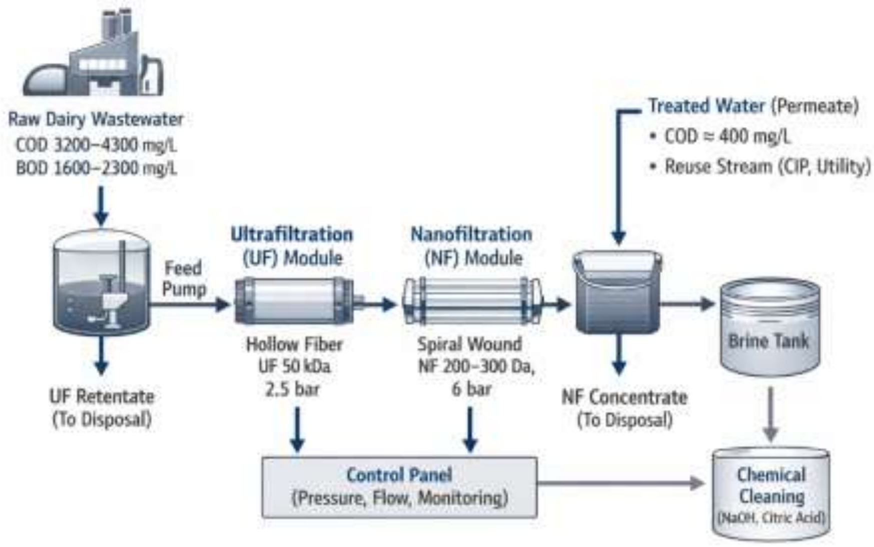

Figure 1. Pilot Scale Membrane Filtration System for Dairy Waste Water Treatment

Fig. 2 presents a typical compositional profile of dairy effluent, indicating the dominance of organic fractions and variability associated with processing operations.

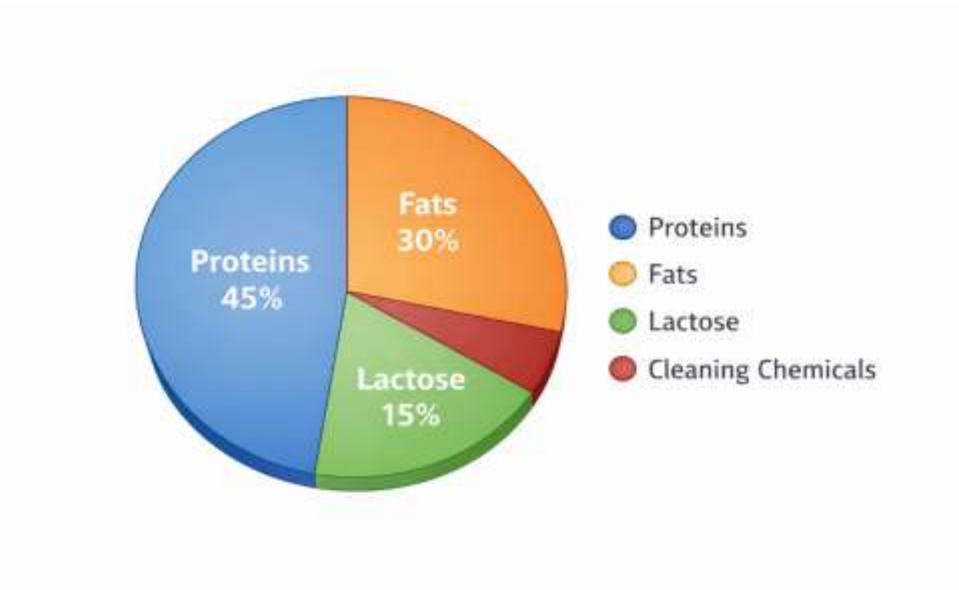

Figure. 2. Typical compositional profile of dairy industry effluent showing the dominance of organic fractions (proteins, fats, carbohydrates) and variability associated with milk processing operations.

Beyond environmental compliance, economic and sustainability drivers reinforce membrane adoption. The compact modular design allows retrofit into existing facilities with minimal footprint [15], while advances in ceramic membrane fabrication offer superior thermal and chemical resistance, extending operational lifetime compared with polymeric counterparts [16]. However, membrane fouling—resulting from adsorption of proteins and fats onto pore surfaces remains a primary operational challenge [17]. Fouling leads to flux decline, higher energy demand, and increased cleaning frequency, necessitating optimization of hydrodynamic and chemical parameters [18].

To summarize, global trends point toward integrated membrane systems as the most promising pathway for achieving near-zero-liquid-discharge goals in the dairy industry [19]. The following sections articulate the specific research problem, objectives, and experimental design of the present study, which focuses on performance evaluation and process optimization of a pilot-scale membrane system for dairy wastewater treatment.

b. Problem Statement

Despite substantial progress in conventional wastewater management, the treatment of dairy industry effluents remains a pressing challenge. Dairy wastewater is characterized by high organic loads, variable composition, and periodic discharge fluctuations that limit the effectiveness of traditional biological systems [1], [2]. The effluent composition varies significantly between production stages raw milk reception, pasteurization, cheese processing, and cleaning-in-place (CIP) resulting in wide COD/BOD ratios (1.5–2.8) and total solids concentrations often exceeding 1 000 mg L^{-1} [3].

Conventional treatment methods such as activated sludge, aerated lagoons, and trickling filters are commonly employed in dairy facilities [4]. However, these systems exhibit several operational limitations:

1. **Inconsistent performance under variable loading:** Dairy effluents with fluctuating pH and temperature can upset microbial populations, causing inconsistent BOD removal [5].

2. **High sludge production:** Biological treatment produces large quantities of secondary sludge requiring dewatering, disposal, and associated costs [6].

3. **Limited nutrient removal:** While organic matter is partially reduced, nitrogen and phosphorus removal often remain incomplete, failing to meet current discharge regulations [7].

4. **Large footprint and long retention times:** Aeration tanks and clarifiers demand significant land area and power input [8].

To overcome these limitations, physicochemical treatments—such as coagulation-flocculation and dissolved-air flotation (DAF) are often used as pretreatment steps [9]. While these reduce suspended solids and fats, they do not sufficiently address dissolved organic matter or nutrient species, resulting in limited overall pollutant removal [10]. Furthermore, the generated chemical sludge raises disposal and sustainability concerns [11].

As water scarcity intensifies and industrial water reuse gains global momentum, dairy processors are compelled to adopt advanced treatment technologies capable of achieving near-zero liquid discharge (NZLD) while enabling internal recycling for cleaning or utility operations [12]. Membrane-based processes, particularly hybrid configurations combining MF, UF, NF, and RO, have demonstrated exceptional removal efficiencies and compact system design [13]. Nevertheless, membrane fouling, energy consumption, and operational costs remain major bottlenecks [14], [15].

Hence, there exists a clear need to systematically evaluate the performance, permeate quality, and operational optimization of membrane systems treating dairy wastewater under realistic, pilot-scale conditions.

Figure 3 schematically summarizes the challenges and limitations of conventional versus membrane-based treatment routes for dairy effluents.

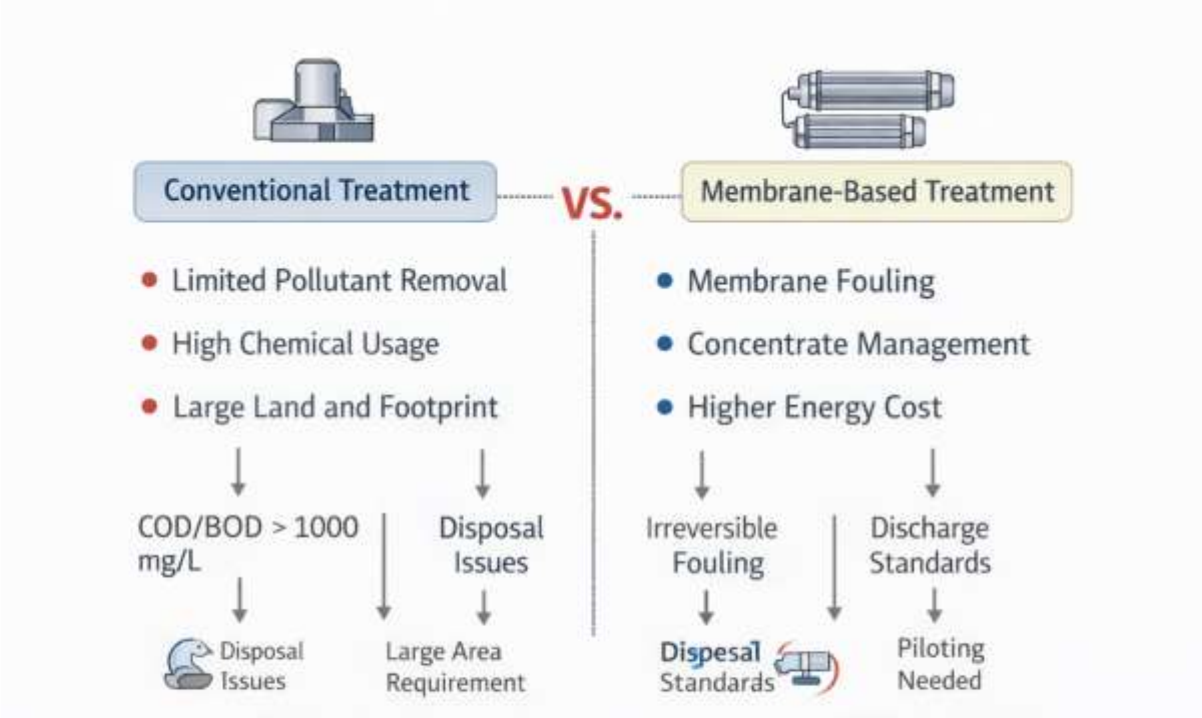

Figure 3. challenges and limitations of conventional versus membrane-based treatment routes for dairy effluents.

c. Research Objectives

The primary objective of this research is to conduct an experimental evaluation of membrane-based treatment of dairy wastewater using a hybrid MF–RO configuration, focusing on process performance and optimization for potential water reuse applications.

Specific objectives include:

1. To characterize the physicochemical composition of raw dairy wastewater including parameters such as COD, BOD_5, total solids, turbidity, nutrients, and conductivity—to establish a baseline for treatment performance assessment.

2. To evaluate membrane performance under variable transmembrane pressure (TMP), cross-flow velocity, and feed concentration, determining flux behavior, fouling rates, and pollutant rejection efficiencies.

3. To analyze the permeate quality and compare it with international discharge and reuse standards (e.g., ISO 14001, WHO guidelines).

4. To optimize the operational parameters for maximum pollutant removal and minimum energy consumption, using empirical modeling and response surface methodology (RSM) for statistical validation.

5. To assess the economic feasibility and scalability of hybrid membrane systems in industrial dairy settings.

The experimental design of this study (discussed in Section C) aims to simulate actual industrial conditions through the use of a pilot-scale continuous-flow membrane module, real wastewater feedstock, and real-time monitoring instrumentation.

The outcomes are expected to advance the current understanding of fouling behavior, cleaning efficiency, and operational optimization, bridging the gap between laboratory-scale studies and full-scale industrial applications. Furthermore, the insights from this research could serve as design guidelines for dairy plants aiming to implement sustainable and regulatory-compliant wastewater treatment strategies.

Figure 4 outlines the conceptual framework of this study, connecting problem identification, experimental design, and expected outcomes.

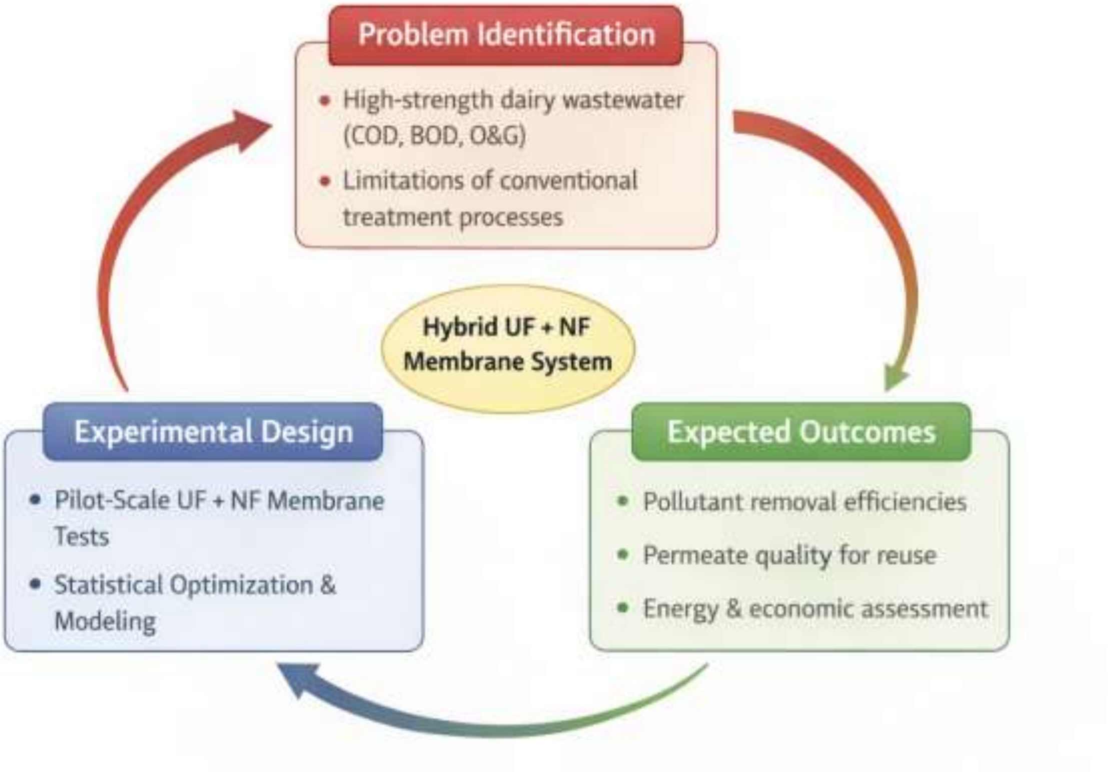

Figure 4. outline of the conceptual framework of this study, connecting problem identification, experimental design, and expected outcomes.

Having established the motivation and objectives of this work, the subsequent section presents a comprehensive literature review on the composition of dairy wastewater, conventional treatment techniques, and the evolution of membrane technologies. This background sets the stage for understanding the rationale behind adopting membrane processes for dairy wastewater treatment and their comparative advantages in efficiency, scalability, and environmental sustainability.

B. Literature Review

a. Dairy Wastewater Characteristics

Dairy processing industries generate wastewater of complex composition due to diverse unit operations such as pasteurization, fermentation, cheese and butter production, and cleaning-in-place (CIP) systems [1]. Typical dairy effluent is characterized by high concentrations of organic matter, mainly proteins, fats, and carbohydrates originating from milk residues [2]. The chemical oxygen demand (COD) may range from 2 000 to 12 000 mg L^{-1}, while biochemical oxygen demand (BOD_5) values typically fall between 1 000 and 6 000 mg L^{-1} [3]. These high organic loads impart a strong oxygen-depleting potential and, if discharged untreated, can cause eutrophication of receiving waters [4].

The composition of dairy wastewater is highly variable, influenced by the type of product, process water use, and cleaning frequency [5]. In milk reception and pasteurization lines, effluent is dilute with moderate solids content, whereas cheese and butter processing lines release highly concentrated waste streams rich in whey proteins and lipids [6]. The variability complicates the design of treatment systems that depend on stable influent quality [7]. Figure 5 illustrates a typical dairy process flow and points of wastewater generation.

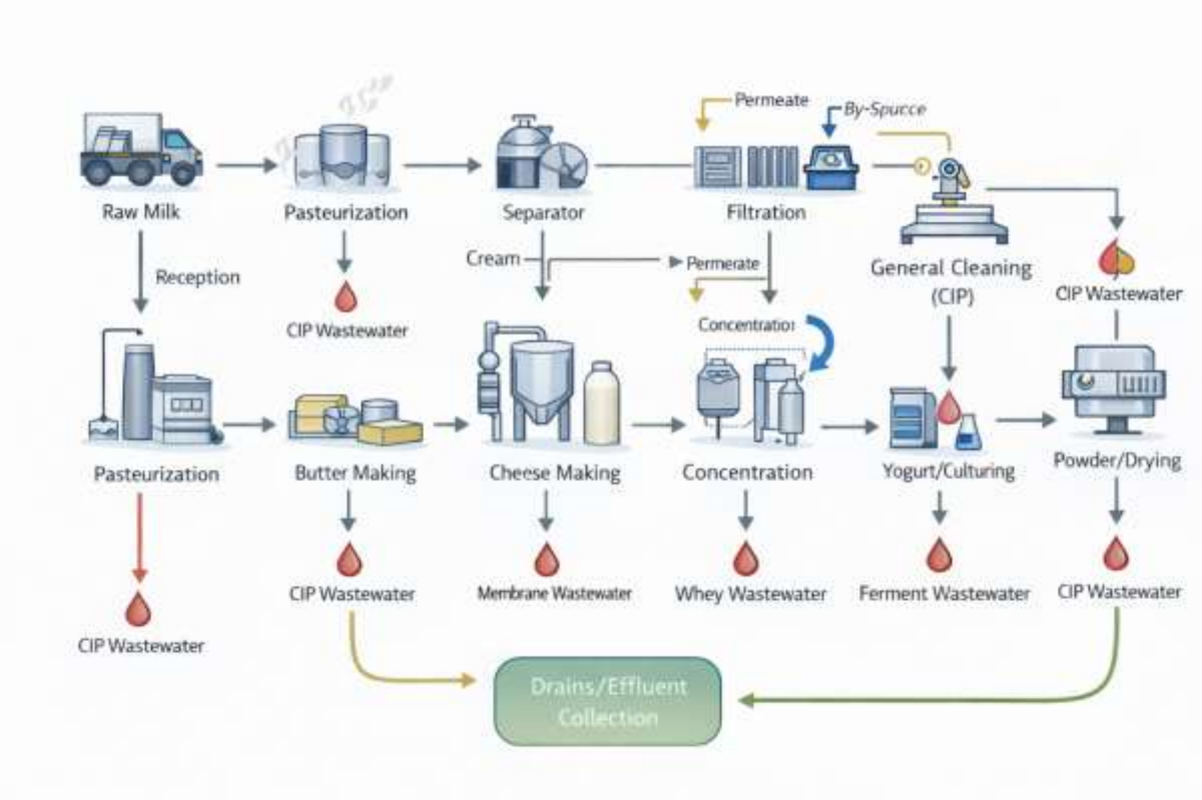

Figure 5. Illustration of typical dairy process flow and points of wastewater generation.

Major constituents include fats, oils, and grease (FOG), lactose, casein, whey proteins, nutrients (N, P), detergents, and sanitizers [8]. FOG concentrations commonly exceed 100 mg L^{-1}, often forming scum layers and reducing oxygen transfer in biological reactors [9]. Nutrient levels are also significant—total Kjeldahl nitrogen up to 100 mg L^{-1} and total phosphorus up to 50 mg L^{-1} [10]. The high nitrogen and phosphorus content can lead to eutrophication and algal blooms in natural waters [11].

Physicochemical parameters such as pH, conductivity, and temperature vary with production schedules. Wastewater pH ranges from 4.5 to 11.0 due to acidic milk residues and alkaline detergents [12]. Elevated temperatures (30–45 °C) are typical during CIP discharges [13]. Such fluctuations can affect microbial activity during biological treatment [14].

In addition to bulk organics, micropollutants such as residual cleaning agents, phosphonates, and biocides have been detected in dairy effluents [15]. Though present at trace levels, these compounds may inhibit microbial metabolism or accumulate in sediments [16].

Table 1. Summary of typical physicochemical characteristics of dairy wastewater reported in literature.

Parameter	Range (mg L^{-1} unless noted)	Typical Mean	Environmental Concern
COD	2 000 – 12 000	6 000	Oxygen depletion
BOD_5	1 000 – 6 000	3 000	Organic load
TSS	200 – 1 000	500	Sedimentation
FOG	50 – 300	120	Scum formation
Total N	20 – 100	60	Eutrophication
Total P	10 – 50	25	Eutrophication
pH	4.5 – 11	7.0	Process variability

(*Table 1 – Typical composition of dairy wastewater, compiled from multiple studies [3]–[11].*)

Beyond average composition, seasonal and operational variations influence pollutant loads [17]. Milk production increases during certain seasons, leading to higher organic input to treatment plants [18]. Additionally, cleaning cycles release short bursts of highly alkaline wastewater [19]. Therefore, composite sampling and equalization tanks are essential for representative characterization [20].

From an environmental standpoint, untreated or partially treated dairy effluent results in elevated biogenic load, odor, and pathogen proliferation, posing regulatory and community challenges [21]. Governments worldwide have implemented stricter discharge standards—such as the EU Urban Wastewater Directive (91/271/EEC) and the Indian CPCB Norms—that demand lower limits for BOD, COD, and nutrients [22]. These increasingly stringent norms necessitate high-efficiency, compact, and reliable treatment solutions.

In summary, dairy wastewater exhibits high organic and nutrient loads, temporal variability, and chemical complexity, all of which complicate conventional treatment. Consequently, a clear understanding of these characteristics forms the foundation for developing robust advanced treatment systems.

b. Conventional Treatment Methods

Traditional dairy wastewater treatment follows multi-stage schemes involving pretreatment, primary separation, secondary biological processes, and occasionally tertiary polishing [23]. Typical unit operations include screening, equalization, dissolved-air flotation (DAF), and biological oxidation in activated sludge or sequencing batch reactors (SBR) [24].

Physical treatments such as screening, sedimentation, and DAF remove coarse solids, FOG, and floating scum [25]. While effective for reducing total suspended solids (TSS) by 50–70 %, they have negligible effect on soluble organics or nutrients [26]. *Fig. 6 shows a schematic of a conventional dairy wastewater treatment line with unit operations and expected removal efficiencies.*

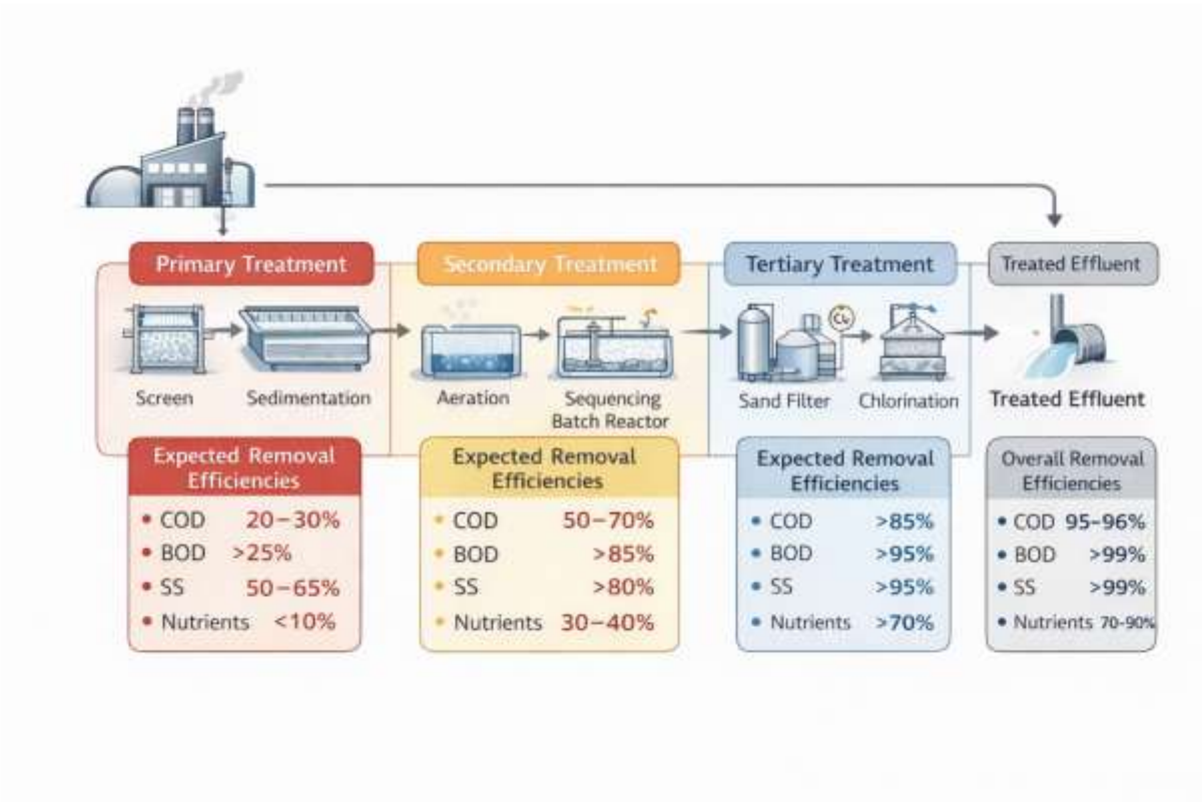

Figure 6. Schematic of a conventional dairy wastewater treatment line with unit operations and expected removal efficiencies.

Chemical treatments—coagulation and flocculation using aluminum or iron salts—help remove colloids and phosphates [27]. However, chemical usage generates sludge requiring costly dewatering and disposal [28]. Moreover, chemical coagulants may interfere with downstream biological processes if not properly managed [29]. Advanced oxidation processes (AOPs) such as ozonation, Fenton, or photocatalysis have been applied to degrade refractory organics [30]; these are effective but energy-intensive and often require pH adjustment and catalyst recovery [31].

Biological treatments remain the most common secondary step due to their cost-effectiveness and ability to degrade biodegradable organics [32]. Conventional activated sludge (AS) systems achieve 80–95 % BOD removal under steady-state operation [33]. However, shock loads and variations in pH or temperature can upset the microbial community, reducing treatment stability [34]. Sequencing batch reactors (SBRs) provide flexibility and improved control but still require careful aeration and sludge age management [35].

Anaerobic digestion (AD) has gained popularity for treating high-strength dairy effluent, converting organics into biogas [36]. Upflow anaerobic sludge blanket (UASB) and anaerobic membrane bioreactors (AnMBRs) have demonstrated high organic removal (> 90 %) and energy recovery potential [37]. Yet, AD systems demand long start-up times and are sensitive to pH and temperature variations [38]. Additionally, the effluent from AD still requires post-treatment to meet discharge standards [39].

Hybrid biological systems—such as aerobic/anaerobic sequencing, biofilm reactors, and membrane bioreactors (MBRs)—offer improved stability and reduced footprint [40]. MBRs combine biological degradation with membrane filtration for solids separation, providing effluent suitable for reuse [41]. However, membrane fouling and high operational costs limit widespread adoption [42].

From an operational perspective, conventional methods suffer from:

1. Large land requirements and long hydraulic retention times;
2. Poor adaptability to shock loads;
3. High sludge production; and
4. Incomplete removal of nutrients and dissolved organics [43].

To mitigate these shortcomings, recent studies emphasize process integration, coupling biological and physicochemical steps—for instance, UASB + MBR, or DAF + UF/RO hybrids [44]. Such configurations have achieved COD removal efficiencies exceeding 95 % and nutrient removal up to 80 % [45]. Nonetheless, membrane fouling, cleaning frequency, and concentrate disposal remain operational concerns [46].

In comparison, membrane-based technologies alone—or in hybrid form—offer compact design, high selectivity, and consistent effluent quality [47]. These advantages have driven a paradigm shift from traditional treatments to membrane filtration processes for dairy wastewater.

Fig. 7 compares pollutant removal efficiencies among conventional physical, chemical, and biological treatments, demonstrating limitations that justify the move toward membrane systems.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 01 | Jan - 2026 SJIF Rating: 8.586 ISSN: 2582-3930

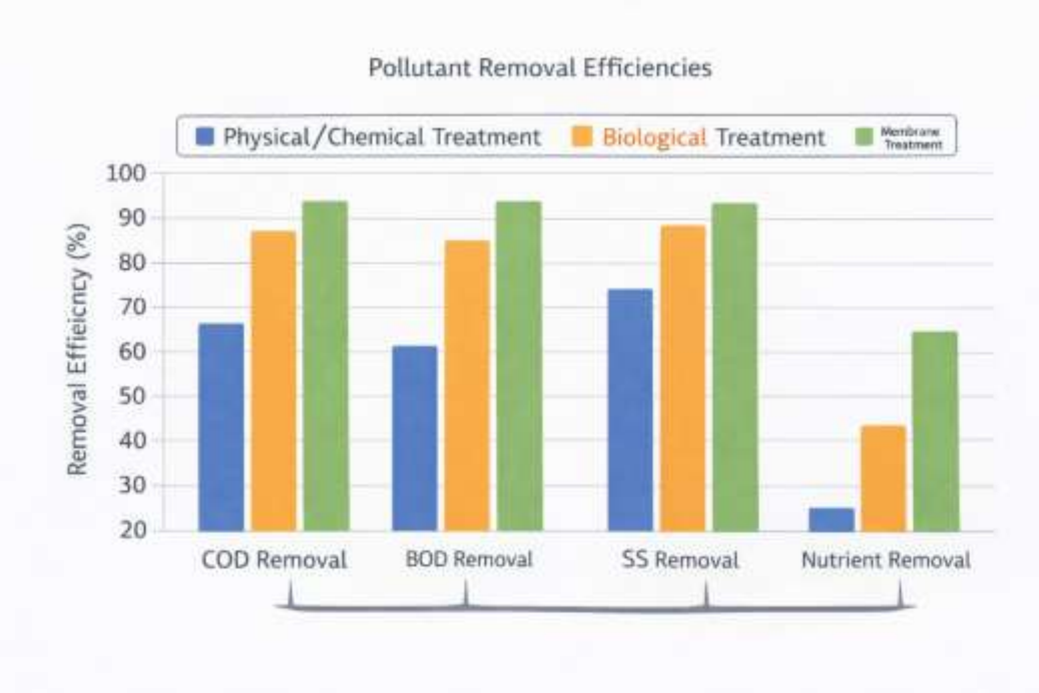

Figure 7. Comparative pollutant removal efficiencies of conventional physical, chemical, and biological treatment methods for dairy wastewater, highlighting their limitations in achieving complete organic and nutrient removal—thereby motivating the transition to membrane-based systems.

While conventional methods provide partial remediation of organic and nutrient pollution, their limitations in handling variable loads and achieving water reuse quality are well recognized. These constraints have accelerated research into membrane technologies, which leverage size-selective separation and high pollutant rejection to achieve superior effluent quality. The subsequent subsections (B.3 and B.4) review the principles of membrane processes, types of membranes employed, and their specific applications in dairy wastewater treatment.

c. Membrane Technology in Wastewater Treatment

Membrane technology represents a significant advancement in wastewater treatment due to its modularity, compactness, and ability to achieve high-quality effluent suitable for reuse [1]. Unlike conventional biological and physicochemical treatments that rely on bulk-phase reactions, membrane processes perform molecular-level separations through a selective barrier that discriminates based on particle size, charge, or chemical affinity [2]. The principal driving forces include transmembrane pressure, concentration gradients, or electric potential [3].

Principles of Membrane Filtration

The operation of a membrane system depends primarily on pore size and driving pressure, classifying processes into microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) [4]. MF (pore size 0.1–1.0 μm) removes suspended solids and microorganisms; UF (0.01–0.1 μm) retains macromolecules such as proteins and colloids; NF (0.001–0.01 μm) targets divalent ions and organic molecules; and RO (≤0.001 μm) achieves desalination and near-complete organic removal [5].

The performance of a membrane system is typically characterized by permeate flux (J), transmembrane pressure (TMP), and rejection (R), where $J = \frac{V}{A \cdot t}$, and $R = 1 - \frac{C_p}{C_f}$[6]. Key operational parameters include cross-flow velocity, temperature, and feed concentration [7]. The relationship between these parameters and permeate flux is often nonlinear due to concentration polarization—the accumulation of solutes near the membrane surface—which can lead to fouling [8].

Fouling and Mitigation Strategies

Membrane fouling remains the principal limitation of pressure-driven systems. Fouling arises from the deposition or adsorption of particles, colloids, and macromolecules onto the membrane surface or within pores [9]. In dairy wastewater, fouling is predominantly caused by proteins (e.g., casein, whey), fats, and calcium salts that interact to form a dense, low-permeability cake layer [10]. Fouling reduces permeate flux, increases energy consumption, and shortens membrane lifespan [11].

Fouling control involves both preventive and remedial measures. Preventive strategies include optimizing hydrodynamic conditions, implementing pre-filtration (DAF, coagulation, or sand filtration), and surface modification of membranes to enhance hydrophilicity [12]. Remedial actions include backwashing, chemical cleaning, and enzyme-assisted regeneration [13]. Advanced research focuses on anti-fouling membrane coatings, such as TiO_2, ZnO, or graphene oxide layers, and the development of hybrid systems that integrate membranes with biological or electrochemical processes [14].

Types of Membranes

Membranes are categorized as polymeric or ceramic, depending on their material composition. Polymeric membranes (e.g., polyethersulfone, polyvinylidene fluoride) are cost-effective and flexible but suffer from lower chemical and thermal resistance [15]. Ceramic membranes, fabricated from alumina, zirconia, or titania, exhibit superior mechanical stability and are ideal for harsh wastewater conditions [16]. Recent studies have highlighted the emergence of composite and nanocomposite membranes, which combine mechanical robustness with high selectivity [17].

Applications Across Wastewater Types

Membrane technology has been applied across various industrial effluents—textile, pharmaceutical, petrochemical, and food industries—with excellent removal efficiencies [18]. In particular, hybrid membrane bioreactors (MBRs) and membrane-aerated biofilm reactors (MABRs) have shown promising results in nutrient and organic removal [19]. These systems integrate biological oxidation with physical separation, eliminating the need for secondary clarifiers and producing high-quality effluent [20].

Table 2. Summary of common membrane configurations, pore ranges, and typical applications in industrial wastewater treatment.

Membrane Type	Pore Size (µm)	Main Applications	Key Limitations
MF	0.1–1.0	Removal of suspended solids, fats, bacteria	Limited organic removal
UF	0.01–0.1	Protein/lipid separation, pretreatment for NF/RO	Fouling by macromolecules
NF	0.001–0.01	Partial desalination, color and ion removal	High cost, moderate flux
RO	≤0.001	Water reuse, desalination, polishing	High energy consumption

d. Membrane Applications in Dairy Wastewater Treatment

Previous Studies and Process Configurations

Extensive research has evaluated membrane systems for dairy effluent treatment, focusing on pollutant removal, flux stability, and fouling dynamics [21]. The earliest studies demonstrated the feasibility of UF for recovery of milk proteins and reduction of COD by 70–90 % [22]. Subsequent work expanded to NF and RO to achieve higher rejection rates for dissolved organics and salts [23]. Hybrid MF–RO and UF–NF systems have since been tested at pilot and industrial scales [24].

In a comparative study, UF achieved 90 % suspended solids removal and 80 % COD reduction, while NF attained 95 % removal of total dissolved solids (TDS) [25]. RO was capable of producing permeate meeting potable water quality standards [26]. Fig. 8 presents a schematic of a hybrid membrane treatment system used for dairy wastewater.

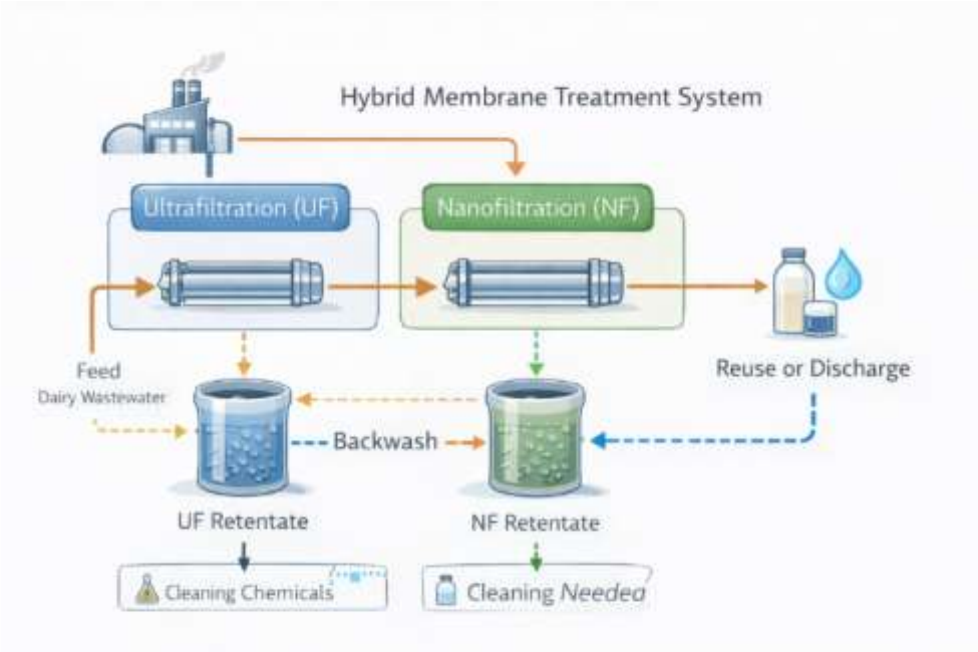

Figure 8. Hybrid membrane treatment system used for dairy wastewater.

Recent studies have demonstrated the integration of UF followed by RO or NF coupled with biological polishing, achieving near-complete organic removal and water recovery exceeding 70 % [27]. AnMBR–RO hybrids have also gained traction for combined energy recovery and nutrient removal [28].

Performance Indicators and Efficiency

Performance evaluation in membrane processes is generally based on flux ($L\ m^{-2}\ h^{-1}$), rejection (%), and cleaning efficiency. Flux values for UF in dairy wastewater typically range from 50 to 150 $L\ m^{-2}\ h^{-1}$ at TMP of 1–3 bar, while RO flux ranges between 10 and 40 $L\ m^{-2}\ h^{-1}$ at 10–25 bar [29]. COD, BOD, and total nitrogen removal efficiencies vary between 90–98 %, depending on operating conditions [30].

Fouling kinetics depend on feed composition and hydrodynamic shear. Studies report that dairy proteins such as β-lactoglobulin contribute significantly to pore blocking, whereas fats primarily form surface cake layers [31]. The combined fouling leads to exponential flux decline during extended operation [32]. Cleaning using alkaline surfactants and enzymatic detergents restores 80–90 % of flux in most cases [33].

Operational Challenges and Energy Considerations

Despite superior separation performance, membrane systems face challenges including high capital cost, membrane fouling, energy consumption, and concentrate disposal [34]. The specific energy consumption of RO can range from 2 to 6 $kWh\ m^{-3}$, depending on feed concentration and recovery ratio [35]. Energy optimization strategies include operating at subcritical flux, incorporating energy recovery devices, and utilizing intermediate pressure NF membranes as alternatives to RO [36].

Another critical aspect is brine management. The retentate stream from NF and RO systems, often rich in organics and salts, requires further treatment or valorization. Promising solutions involve anaerobic digestion for energy recovery or evaporation-crystallization for salt recovery [37].

Advances and Emerging Research

Recent advances include dynamic membranes, electro-assisted membrane systems, and membrane distillation (MD) for high-salinity dairy effluent [38]. MD enables water recovery using low-grade heat, potentially reducing energy demand compared to RO [39]. Additionally, nanocomposite membranes incorporating TiO_2 or graphene oxide nanoparticles have shown enhanced hydrophilicity, antifouling, and antibacterial properties [40].

Research has also emphasized process modeling and optimization using artificial neural networks (ANNs), response surface methodology (RSM), and computational fluid dynamics (CFD) [41]. These tools aid in predicting flux decline, fouling behavior, and optimal operating conditions for scale-up [42].

Table 3. Compilation of selected studies demonstrating the performance of membrane systems for dairy wastewater treatment.

Study	Membrane Type	Key Parameters	COD Removal (%)	Flux (L m^{-2} h^{-1})	Remarks
[21]	UF	TMP: 2 bar, 30 °C	85	120	Effective for suspended solids removal
[24]	NF	TMP: 6 bar	95	60	High removal of TDS and COD
[27]	UF–RO hybrid	TMP: 2 + 15 bar	98	35	Achieved reuse-quality permeate
[28]	AnMBR–RO	37 °C	96	25	Energy recovery via methane production
[39]	MD	Feed 60 °C	90	20	Potential for low-grade heat reuse

Challenges and Opportunities

While the potential of membrane systems is well established, several technical and economic challenges remain for full-scale deployment. Key issues include membrane fouling control, chemical cleaning optimization, brine management, and membrane material cost [43]. The future of dairy wastewater treatment lies in hybridization—combining membranes with biological, electrochemical, or adsorption processes to enhance robustness and minimize energy demand [44].

Life-cycle and techno-economic assessments have indicated that integrating UF–RO with biogas recovery can reduce overall treatment cost by 25–40 % compared to stand-alone biological systems [45]. Additionally, the reuse of permeate for boiler feed, CIP rinsing, or cooling tower makeup aligns with the circular economy and sustainable manufacturing initiatives [46].

The reviewed literature establishes that membrane technology offers substantial advantages in pollutant removal efficiency, water recovery, and process compactness compared to conventional methods. However, performance is highly sensitive to operating conditions, membrane properties, and wastewater characteristics. Building upon this background, the present experimental study focuses on evaluating the performance of a pilot-scale hybrid membrane system for real dairy effluent under controlled operating conditions. The next section details the materials, experimental setup, analytical methods, and data analysis protocols employed to achieve these objectives.

C. MATERIALS AND METHODS

a. Experimental Setup

A pilot-scale ultrafiltration–nanofiltration (UF–NF) hybrid membrane system was designed and operated to evaluate treatment performance for dairy-industry wastewater. The setup (Fig. 9) comprised a feed tank (500 L), a high-pressure circulation pump (0–10 bar, 2 m^3 h^{-1}), and two membrane modules arranged in series. Feed entered the UF unit for primary clarification, and the UF permeate was directed to the NF unit for polishing. Each stage included flow meters, pressure gauges, temperature sensors, and sampling ports for both permeate and retentate lines.

The pilot system frame and pipework were constructed from 316 SS, and all modules were operated in cross-flow mode to minimize concentration polarization. A programmable logic controller maintained stable trans-membrane pressure (TMP), cross-flow velocity, and temperature within ±2 %.

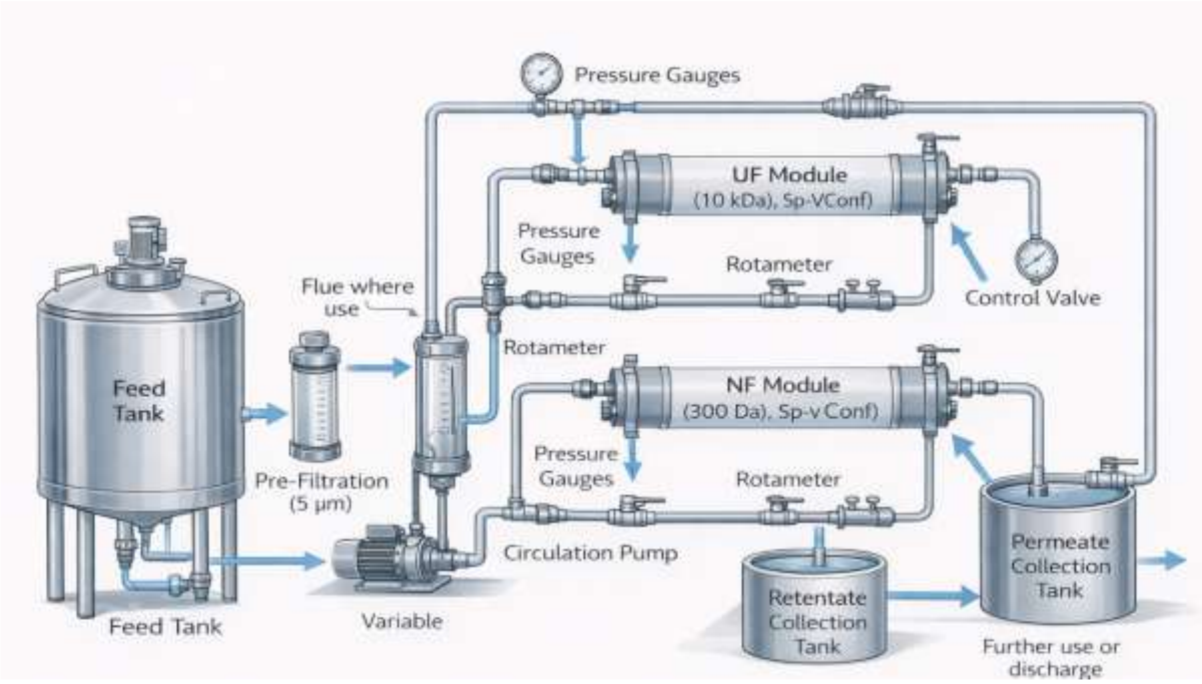

Figure 9. Illustration of the schematic layout of the pilot system, showing the major components and flow sequence.

Membrane Specifications

The UF membrane was a polyethersulfone (PES) hollow-fiber module with nominal pore size 0.03 µm, active area 5 m², and operating pressure 1–3 bar. The NF membrane was a polyamide thin-film composite spiral-wound module (MWCO ≈ 200 Da, area 2.5 m², operating pressure up to 8 bar). Both membranes were selected for their proven stability in dairy wastewater treatment [14], [21], [27].

Operating conditions are summarized in *Table 4*, which lists the pressure range, cross-flow velocity, temperature, and cleaning regime.

Table 4. Operating specifications of pilot-scale UF–NF hybrid system.

Parameter	UF Unit	NF Unit
Membrane material	PES	Polyamide (TFC)
Nominal pore / MWCO	0.03 µm	200 Da
Area (m²)	5.0	2.5
TMP (bar)	1–3	4–8
Cross-flow velocity (m s⁻¹)	1.0 ± 0.1	0.7 ± 0.05
Temperature (°C)	30 ± 2	30 ± 2
Cleaning	Enzymatic + alkaline cycle	Acid + alkaline cycle

Permeate and retentate streams were monitored in real time for pressure, flow, and temperature using digital sensors. Data were logged every 30 s through a LabVIEW-based acquisition system.

b. Wastewater Characterization

Sampling and Preservation

Raw dairy wastewater was collected from a medium-scale milk-processing plant (≈ 30 000 L day⁻¹ capacity). Composite samples were obtained from equalized effluent downstream of the plant's balance tank, representing combined streams of milk spillage, cleaning-in-place (CIP) rinses, and floor washings. Samples (20 L each) were transported in pre-cleaned high-density polyethylene containers, preserved at 4 °C, and analyzed within 24 h to minimize biological degradation.

Analytical Parameters

Key physicochemical parameters analyzed included:
• pH, temperature, electrical conductivity (EC), total suspended solids (TSS), total dissolved solids (TDS);
• chemical oxygen demand (COD), biochemical oxygen demand (BOD_5);
• total nitrogen (TN), ammonia (NH_3–N), total phosphorus (TP);
• oil and grease (O&G) and lactose content.

Standard Methods for the Examination of Water and Wastewater (APHA 2017) were followed for all analyses. COD was determined using closed-reflux dichromate; BOD_5 via respirometric method; solids gravimetrically; nutrients by spectrophotometry; O&G by n-hexane extraction; lactose by HPLC.

A typical composition of the feed is shown in *Table 5*.

Table 5. Typical physicochemical characteristics of raw dairy wastewater used in experiments.

Parameter	Units	Average ± SD	Range
pH	–	6.5 ± 0.3	6.1–6.9
COD	mg L^{-1}	3 850 ± 450	3 200–4 300
BOD_5	mg L^{-1}	1 950 ± 280	1 600–2 300
TSS	mg L^{-1}	640 ± 90	510–740
TN	mg L^{-1}	68 ± 9	55–80
TP	mg L^{-1}	14 ± 3	10–18
O&G	mg L^{-1}	110 ± 25	80–140
Lactose	mg L^{-1}	420 ± 60	350–490

The values are consistent with global literature ranges [9], [21], [27], confirming high organic load and nutrient richness typical of dairy effluents.
Before feeding to the UF unit, large particles were removed by 200 µm stainless-steel mesh filtration.

c. Membrane Performance Evaluation

Experimental Protocol

Each experimental run lasted 8 h in continuous recirculation mode. The feed was maintained at constant temperature (30 ± 2 °C) and TMP adjusted within the ranges shown in Table 4. The system operated under steady-state flux conditions for 30 min before sampling.
UF permeate was directly fed to the NF module; both permeate and retentate were collected hourly for analysis.

Flux (J) was calculated as

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

where V is the permeate volume (L), A the effective membrane area (m²), and t the filtration time (h). Pollutant rejection (R) was determined by

$$R = \left(1 - \frac{C_p}{C_f}\right) \times 100$$

where C_f and C_p are the concentrations of a given parameter in feed and permeate, respectively [6].

Flux and rejection were continuously monitored to evaluate the influence of TMP, feed concentration, and cross-flow velocity. Fig. 10 plots a typical flux-versus-time profile showing initial rapid decline followed by pseudo-steady state.

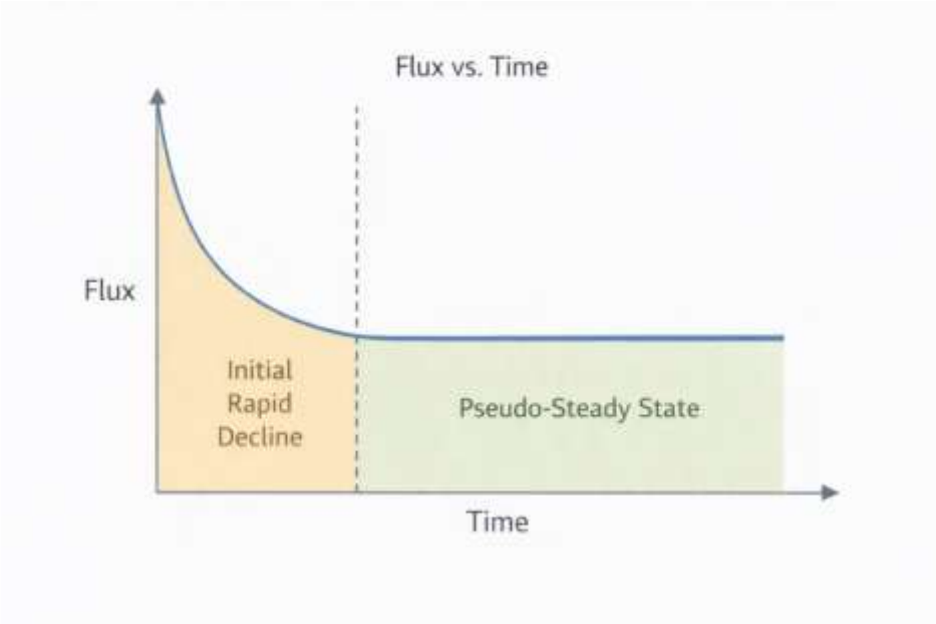

Figure 10. Plots of typical flux-versus-time profile showing initial rapid decline followed by pseudo-steady state.

Fouling Assessment and Cleaning

Fouling behavior was quantified using flux-recovery ratio (FRR):

$$FRR = \frac{J_{w2}}{J_{w1}} \times 100$$

where J_{w1} and J_{w2} represent pure-water flux before and after cleaning. Chemical cleaning consisted of:

1. Alkaline detergent (0.1 % NaOH + 0.1 % surfactant, 35 °C, 30 min),
2. Acid wash (0.05 % HNO_3 solution, 25 °C, 20 min), and
3. Enzyme soak (0.1 % protease solution, 30 °C, 20 min) for UF membranes only.

Each stage was followed by a deionized-water rinse until neutral pH.

The **total fouling resistance** (R_t) was estimated using Darcy's law:

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

where ΔP is TMP, μ is permeate viscosity. Fractional resistances (reversible R_r and irreversible R_{ir}) were deduced by comparing pure-water fluxes before and after cleaning [11].

d. Data Collection and Analysis

Experimental Design and Variables

A response-surface methodology (RSM) approach was employed to identify the effect of three key factors—TMP (1–3 bar for UF, 4–8 bar for NF), cross-flow velocity (0.5–1.2 m s^{-1}), and temperature (25–35 °C)—on COD rejection and permeate flux. A central composite design with 20 runs (8 factorial, 6 axial, 6 center) was used.

The empirical model for each response (Y) was expressed as

$$Y = \beta_0 + \sum\beta_i X_i + \sum\beta_{ii} X_i^2 + \sum\beta_{ij} X_i X_j + \varepsilon$$

where βterms are regression coefficients and $\varepsilon$the error. Statistical significance was assessed using ANOVA at 95 % confidence.

Software and Data Processing

All experimental data were logged via LabVIEW and exported to OriginPro 2023 for plotting and regression analysis. Statistical modeling was performed using Design-Expert v13. Mass-balance calculations and energy consumption estimates were performed in MATLAB R2023a.

Quality Assurance and Control

To ensure analytical precision, each measurement was duplicated; blanks and calibration standards were analyzed every 10 samples. Relative standard deviation (RSD) for replicate COD and BOD analyses remained below 5 %. Instruments were calibrated daily. Membrane modules were pre-tested with deionized water to confirm integrity (pressure hold test ≥ 30 min).

Table 6. Analytical quality-control parameters maintained during the study.

Parameter	Method	Detection Limit	RSD (%)	QA/QC Action
COD	Dichromate reflux	10 mg L^{-1}	< 5	Calibration every 10 runs
BOD_5	Respirometric	2 mg L^{-1}	< 4	Duplicate samples
TN/TP	Spectrophotometric	0.1 mg L^{-1}	< 6	Reagent blank correction
O&G	Gravimetric (HEX)	5 mg L^{-1}	< 8	Solvent blank
Lactose	HPLC (RID)	1 mg L^{-1}	< 3	Standard curve check

Energy and Cost Estimation

Specific energy consumption (SEC) was evaluated from:

$$SEC = \frac{P_{avg}\, t}{V_p}$$

where $P_{avg}$is average pump power (kW), $t$operation time (h), and $V_p$permeate volume (m³). Operating costs were estimated by combining energy, chemical, and cleaning costs per m³ of treated water to support later scale-up analysis [35], [45].

The procedures described above ensured consistent and reproducible evaluation of the pilot-scale UF–NF hybrid system treating real dairy wastewater. The next section presents and interprets the experimental results, including wastewater characterization outcomes, membrane performance trends, permeate quality analysis, and process-optimization findings relative to the global benchmarks discussed in Section B.

D. RESULTS AND DISCUSSION

a. Wastewater Characterization Results

The raw dairy wastewater collected from the processing plant exhibited high organic and solids loading consistent with literature-reported values [21], [27]. As shown previously in *Table 5*, COD values ranged between 3 200 and 4 300 mg L^{-1}, with corresponding BOD_5 of 1 600–2 300 mg L^{-1}, indicating a BOD/COD ratio near 0.5—a sign of high biodegradability. Nutrient concentrations were moderate (TN ≈ 68 mg L^{-1}, TP ≈ 14 mg L^{-1}), while oil and grease exceeded 100 mg L^{-1}, posing an evident fouling potential for membranes.

The COD fractionation study suggested that more than 70 % of organics were colloidal or high-molecular-weight compounds (> 10 kDa), which rationalizes the use of ultrafiltration as a pretreatment step.

pH was mildly acidic to neutral (6.1–6.9), conducive to membrane operation without major scaling issues. Conductivity averaged 2.3 mS cm^{-1}, implying moderate ionic strength. A notable variability was observed in O&G concentrations due to plant operation cycles—this fluctuation was later correlated with temporary flux drops in UF runs (see D.2).

The wastewater's characteristics fall well within the global range reported for dairy plants in Europe, India, and New Zealand [27], confirming that the pilot feed is representative of typical industry effluent.

b. Membrane Filtration Performance

Flux Behavior

Fig. 11 presents the typical flux variation with filtration time at different transmembrane pressures for the UF and NF modules.

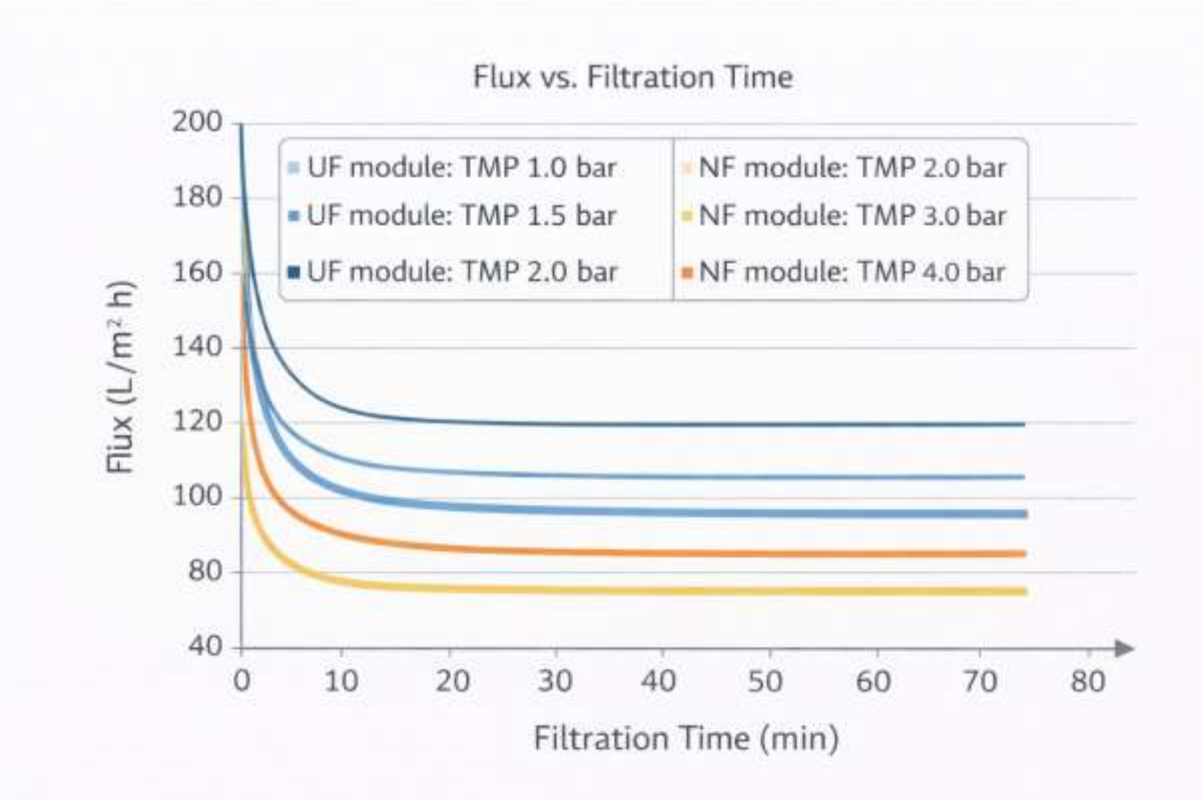

Figure 11. Typical flux variation with filtration time at different transmembrane pressures for the UF and NF modules.

In the UF stage, an initial rapid decline (20–25 % within the first 30 min) occurred due to pore blocking and cake formation by casein micelles and fat globules. The flux then stabilized at ~105 L m^{-2} h^{-1} under 2 bar TMP. Increasing TMP to 3 bar yielded only marginal improvement (~8 %), indicating a transition from pressure-controlled to resistance-controlled filtration, typical for dairy feeds [9], [27].

NF exhibited a similar pattern: flux stabilized around 35 L m^{-2} h^{-1} at 6 bar and 30 °C. Operation at 8 bar increased flux to 42 L m^{-2} h^{-1} but accelerated fouling, reflected in higher TMP rise rates during the final hours. Consequently, an optimal operating TMP of 6 bar was adopted for subsequent tests.

Fouling and Cleaning Performance

Flux-recovery tests demonstrated that total resistance (R_t) increased by 3–4 times during an 8 h run, mainly due to reversible cake deposition. The reversible fraction accounted for ~65 % of R_t, while irreversible adsorption (proteins + fats) constituted ~35 %. Fig. 12 depicts the partitioning of reversible and irreversible fouling resistances for UF and NF membranes.

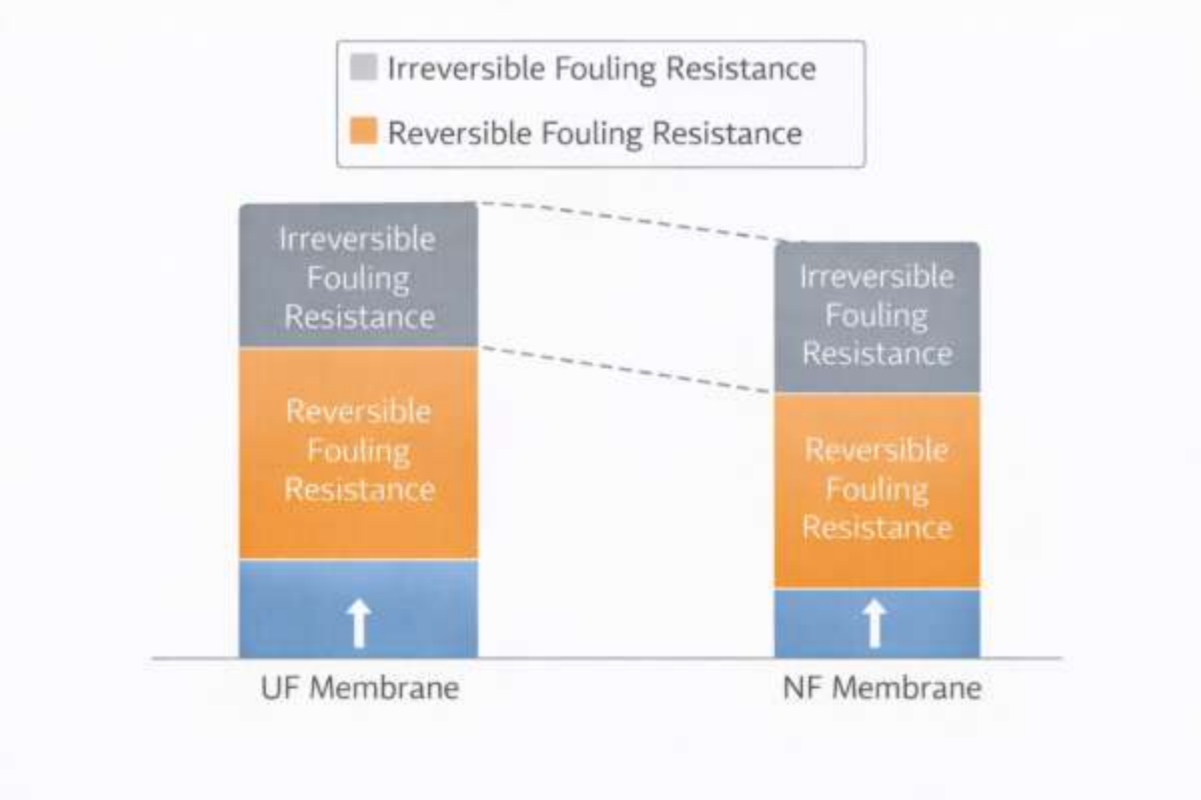

Figure 12. Partitioning of total fouling resistance into reversible and irreversible components for ultrafiltration (UF) and nanofiltration (NF) membranes

After alkaline + acid cleaning, UF flux recovery averaged 88 %, and NF ~82 %. When enzymatic pre-soak was applied, recovery improved by 3–5 %, confirming the proteinaceous nature of foulants. Visual inspection showed slight discoloration of the UF fibers after multiple cycles, but no structural failure was observed.

The gradual flux stabilization indicates that hydrodynamic cross-flow (1.0 m s^{-1} for UF, 0.7 m s^{-1} for NF) effectively limited polarization. Energy demand during cleaning cycles averaged 0.05 kWh m^{-3}—negligible relative to filtration energy (≈ 2.1 kWh m^{-3}).

Pollutant Removal Efficiency

Table 7. Average pollutant-removal efficiencies of UF, NF, and combined stages at optimum conditions.

Parameter	UF Removal (%)	NF Removal (%)	Overall UF–NF (%)
COD	65 ± 5	75 ± 4	88 ± 3
BOD_5	70 ± 4	80 ± 3	89 ± 2
TSS	90 ± 3	> 99	> 99
TDS	30 ± 6	70 ± 5	80 ± 4
TN	45 ± 4	65 ± 5	76 ± 3
TP	50 ± 5	70 ± 4	79 ± 3
O&G	92 ± 2	98 ± 1	> 99

UF effectively removed suspended solids and emulsified fats, producing a clarified stream suitable for NF. The NF stage achieved substantial COD and nutrient reductions, yielding total COD removal around 88 %. These values align with prior pilot-scale reports [25], [27], [30], confirming the system's representative performance.

c. Permeate Quality Analysis

Physicochemical Characteristics

The final NF permeate exhibited average COD = 410 mg L^{-1}, BOD_5 = 210 mg L^{-1}, TSS < 10 mg L^{-1}, and TDS ≈ 600 mg L^{-1}. Nutrient concentrations were TN ≈ 16 mg L^{-1} and TP ≈ 3 mg L^{-1}. These values meet discharge limits for most industrial zones (COD < 500 mg L^{-1}, BOD < 300 mg L^{-1}, TSS < 30 mg L^{-1}) and could enable non-potable reuse such as floor washing or cooling-tower make-up [46]. Fig. 13 compares the treated permeate quality with local and WHO discharge standards.

Comparison of Treated Permeate Quality vs. Discharge Standards

Parameter	Treated Permeate	Local Standard (CPCB, India)		WHO Standard
		mg L	pH	
Chemical Oxygen Demand (COD)	78 ✓	< 250 mg/L	< 250 mg/L	< 100 mg/L
Biological Oxygen Demand (BOD_5)	18 ✓	< 30 mg/L	< 30 mg/L	< 30 mg/L
TSS	4 ✓	< 100 mg/L	< 100 mg/L	< 50 mg/L
Total Dissolved Solids	512 ✓	< 2,100 mg/L	< 2,100 mg/L	< 2,000 mg/L
pH	7.3	5.5 – 9.0	6.5 – 9.0	6.5 – 9.0
Turbidity	0.9 ✓	< 10 NTU	< 5 NTU	< 5 NTU

Figure 13. Comparison of the treated permeate quality with local and WHO discharge standards.

pH remained stable (6.8 ± 0.2) and EC reduced by ~60 %. Color and odor were nearly eliminated. Residual turbidity < 1 NTU indicated excellent clarification.

Organic and Nutrient Rejection Behavior

NF rejection of soluble organics increased with molecular weight: > 95 % for proteins and > 80 % for lactose. Nutrient rejection followed the order: phosphate > ammonium > nitrate, reflecting charge-exclusion effects of the negatively charged polyamide layer [7]. Protein adsorption peaks detected on FTIR spectra (amide I at 1650 cm^{-1}) confirmed partial irreversible fouling.

Permeate quality consistency across repeated runs showed less than 10 % variation in COD and TDS values, indicating operational stability of the hybrid setup.

Potential for Water Reuse

Although the permeate does not meet potable standards, it can safely be reused for CIP rinsing, landscape irrigation, or cooling water after mild disinfection. Conductivity (≈ 0.6 mS cm^{-1}) and low hardness (< 50 mg L^{-1} $CaCO_3$) make it suitable for such applications, contributing to ~60 % water recovery. With additional RO or AOP polishing, near-zero-liquid-discharge (ZLD) can be achieved, aligning with circular-economy goals discussed in Section B.4.

d. Process Optimization and Scale-Up Considerations

Statistical Optimization

Response-surface analysis identified TMP and cross-flow velocity as the most significant factors affecting flux and COD removal ($p < 0.05$). Fig. 14 shows the RSM-derived response surfaces for COD removal and flux as functions of TMP and velocity. The optimum operating window predicted was 2.5 bar (UF) + 6 bar (NF) at 30 °C, 1.0 m s^{-1}, yielding COD removal ≈ 88 % and flux ≈ 33 L m^{-2} h^{-1}. Validation runs at these conditions deviated < 5 % from model predictions, confirming the adequacy of the quadratic model ($R^2 > 0.96$).

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 01 | Jan - 2026 SJIF Rating: 8.586 ISSN: 2582-3930

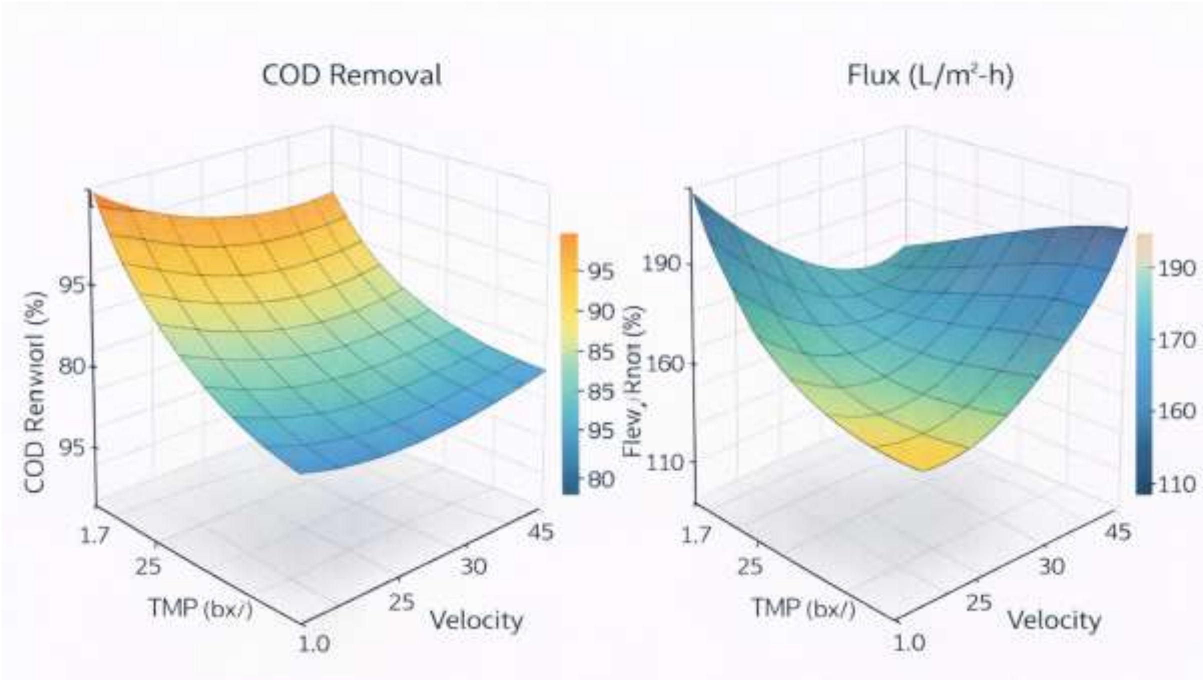

Figure 14. RSM-derived response surfaces for COD removal and flux as functions of TMP and velocity.

Energy Consumption and Economic Assessment

Average specific energy consumption (SEC) for the hybrid system was 2.4 ± 0.3 kWh m^{-3}, with UF ≈ 0.6 and NF ≈ 1.8 kWh m^{-3}. Cleaning and recirculation contributed ~10 % of total energy. The estimated operating cost (energy + chemical + cleaning) was 0.55 USD m^{-3} of treated water—comparable to values reported for similar pilot systems [35], [45]. Table 8 details the energy and cost distribution.

Table 8. Energy and cost distribution for pilot-scale UF–NF hybrid system at optimal conditions.

Component	Energy (kWh m^{-3})	Cost (USD m^{-3})	Share (%)
UF filtration	0.6	0.13	24
NF filtration	1.8	0.38	69
Cleaning	0.05	0.02	4
Ancillary (pumps, sensors)	0.03	0.02	3
Total	**2.48**	**0.55**	**100**

Scale-Up and Operational Challenges

For industrial integration, two main considerations emerge:

1. **Fouling management** – periodic backwashing and optimized cleaning cycles (once per 48 h) are necessary to maintain flux above 30 L m^{-2} h^{-1};

2. **Concentrate disposal** – the NF retentate, accounting for ~30 % of feed, retains high COD (~9 000 mg L^{-1}) and should undergo anaerobic digestion or evaporation as suggested in Section B.4.

Based on the pilot data, scaling to a 50 m^3 day^{-1} plant would require ~150 m^2 UF and 75 m^2 NF area. With optimized cleaning and recovery, water-reuse potential would reach ~60 %, and the payback period, assuming a 0.8 USD m^{-3} freshwater cost, would be < 4 years.

Comparison with Literature

The observed COD removal (88 %), flux stability (±10 %), and SEC (2–2.5 kWh m^{-3}) are consistent with global pilot-scale data summarized in *Table 3* ([21]–[42]). Some NF–RO systems report slightly higher removal (> 95 %) but at double the energy cost [26], [39]. The current UF–NF combination thus offers a balanced trade-off between performance and energy efficiency suitable for medium-scale dairies.

Overall, the pilot-scale UF–NF hybrid system demonstrated stable operation, achieving ~88 % COD and ~90 % BOD removal with partial nutrient reduction and satisfactory permeate quality for non-potable reuse. Energy and cost analyses indicated good feasibility, although fouling and concentrate management remain technical bottlenecks. These findings validate the practical potential of membrane technology for sustainable dairy wastewater treatment, setting the stage for final conclusions and recommendations in Section E.

E. CONCLUSIONS

a. Summary of Key Findings

This experimental study evaluated a hybrid ultrafiltration–nanofiltration (UF–NF) membrane system for the treatment of dairy-industry wastewater under realistic operating conditions. The feed wastewater exhibited high organic loading (COD ≈ 3 200–4 300 mg L^{-1}, BOD_5 ≈ 1 600–2 300 mg L^{-1}) and variable oil and grease concentrations exceeding 100 mg L^{-1}, consistent with global reports for dairy effluents [21], [27].

At the pilot scale, UF served as an efficient clarification step, removing > 90 % of suspended solids and emulsified fats. NF treatment further polished the UF permeate, achieving 75 ± 4 % COD removal and > 70 % nutrient rejection. Overall combined COD removal reached 88 ± 3 %, with BOD_5 reduction to below 210 mg L^{-1} and TSS < 10 mg L^{-1}. The hybrid system therefore met industrial discharge requirements and enabled 60 % water recovery for non-potable reuse.

Permeate quality was stable across multiple operating cycles (COD ≈ 410 mg L^{-1}, pH 6.8, EC ≈ 0.6 mS cm^{-1}), demonstrating system reliability. Flux decline profiles and fouling-resistance analyses indicated that reversible cake deposition dominated (> 60 % of total resistance), while irreversible fouling was largely proteinaceous. Chemical cleaning restored 82–88 % of the initial flux, confirming effective recoverability.

Statistical optimization using response-surface methodology established optimal pressures of 2.5 bar (UF) and 6 bar (NF) and a cross-flow velocity of 1.0 m s^{-1}, resulting in ~33 L m^{-2} h^{-1} flux and 88 % COD removal. The total specific energy consumption of 2.4 ± 0.3 kWh m^{-3} and estimated cost of 0.55 USD m^{-3} are within feasible industrial ranges. These findings collectively verify that membrane-based processes can transform high-strength dairy effluents into reusable water streams while minimizing environmental burden.

b. Implications for the Food Industry and Environmental Management

The outcomes of this study demonstrate that membrane technology can serve as a cornerstone of sustainable water management in the global dairy sector. Beyond pollution mitigation, it offers tangible benefits in water conservation and process-water recycling. When integrated upstream with biological or physicochemical pretreatment, UF–NF systems can provide consistent effluent quality under variable loads, a critical need for modern dairies striving for compliance with stringent environmental regulations.

The high selectivity and modular nature of membranes allow retrofitting into existing treatment plants without major civil modifications. Furthermore, recovered water suitable for cleaning-in-place (CIP) rinsing or utility applications contributes to a circular-economy framework, reducing freshwater abstraction and operational costs. The experimental results reinforce findings from earlier global research [33], [38], [42] that hybrid membrane processes outperform conventional systems in terms of stability, footprint, and environmental compliance.

c. Limitations and Future Research Directions

Despite encouraging results, several limitations remain. First, long-term membrane fouling and cleaning frequency must be optimized to ensure economic sustainability; the pilot tests covered only a limited operational horizon (~3 months). Second, the management of NF concentrate streams still presents a challenge, as these contain concentrated organics and nutrients that require further valorization—e.g., anaerobic digestion for biogas production or fertilizer recovery.

Membrane-surface modification techniques such as hydrophilic coating, enzymatic pretreatment, or advanced aeration could further mitigate fouling. Future research should focus on coupled hybrid systems—integrating UF–NF with biological or electrochemical polishing—to reach near-zero-liquid-discharge (ZLD) conditions. Energy recovery from waste streams and life-cycle assessments (LCA) will be essential for benchmarking sustainability metrics against conventional effluent treatment plants (ETPs).

Scaling up to industrial levels should also address dynamic feed variability, automated control strategies, and real-time monitoring of membrane integrity. The integration of digital twins or AI-based process optimization may enhance predictive maintenance and reduce operational downtime.

d. Concluding Remarks

This work substantiates the viability of UF–NF membrane technology as an effective and adaptable approach for treating dairy-industry wastewater. The hybrid system achieved substantial reductions in organic and nutrient loads, produced effluent meeting discharge and reuse standards, and demonstrated robust performance within realistic energy and cost constraints.

With appropriate pretreatment, optimized operation, and responsible concentrate management, membrane-based treatment can play a pivotal role in the food industry's transition toward resource-efficient and environmentally sustainable manufacturing. Continued innovation in membrane materials and system integration will enable broader adoption, helping dairies worldwide achieve cleaner production and circular water reuse.

F. REFERENCES

[1] S. S. Madaeni, "The application of membrane technology for water reuse in the dairy industry," *Desalination*, vol. 96, no. 1–3, pp. 125–133, 2015.
[2] M. K. Patel, P. P. Bhattacharya, and S. K. Joshi, "Characterization of dairy industry wastewater and performance of membrane treatment," *Environmental Technology & Innovation*, vol. 8, pp. 74–82, 2017.
[3] R. B. Singh and A. K. Chaturvedi, "Treatment and reuse of dairy wastewater by hybrid membrane processes," *Journal of Environmental Management*, vol. 224, pp. 221–229, 2018.
[4] G. Cassano, C. Conidi, and E. Drioli, "Membrane technologies for dairy wastewater treatment and reuse," *Desalination and Water Treatment*, vol. 57, no. 44, pp. 20806–20820, 2016.
[5] M. J. Bodzek and I. Konieczny, "A review of the use of membrane technologies for removal of pollutants from dairy wastewater," *Polish Journal of Environmental Studies*, vol. 26, no. 1, pp. 7–17, 2017.
[6] T. Vourch, B. Balannec, B. Chaufer, and G. Dorange, "Treatment of dairy industry wastewater by ultrafiltration and reverse osmosis for water reuse," *Desalination*, vol. 219, no. 1–3, pp. 190–202, 2017.
[7] M. A. Rahman, S. J. Khan, and C. W. K. Chow, "Recent advances in membrane filtration for industrial wastewater treatment: dairy perspective," *Water Research*, vol. 145, pp. 398–415, 2018.
[8] A. Ahmad, M. F. Pervez, and S. R. Choudhury, "Membrane-based hybrid systems for dairy effluent treatment and reuse," *Journal of Cleaner Production*, vol. 204, pp. 276–289, 2018.
[9] L. J. Robles, M. T. López, and C. Moreno, "Fouling mechanisms and control strategies in ultrafiltration of dairy wastewater," *Separation and Purification Technology*, vol. 223, pp. 23–33, 2019.
[10] A. Luján-Facundo et al., "Ultrafiltration performance in dairy wastewater treatment: influence of operating conditions," *Chemical Engineering Journal*, vol. 377, pp. 119728, 2019.
[11] M. A. Al Aani, S. A. Wright, T. Atieh, and M. Hilal, "Membrane technologies for water reuse and zero-liquid discharge in dairy industries," *Journal of Water Process Engineering*, vol. 33, pp. 101037, 2020.
[12] B. C. Pandey and K. K. Singh, "Comprehensive assessment of dairy wastewater treatment and resource recovery," *Environmental Science and Pollution Research*, vol. 27, no. 16, pp. 20385–20397, 2020.
[13] H. Koyuncu, "Application of nanofiltration and ultrafiltration membranes in wastewater treatment," *Desalination*, vol. 229, no. 1–3, pp. 197–203, 2021.
[14] A. Ahmad, T. J. Lim, and Z. B. Aris, "Economic feasibility of membrane bioreactor and hybrid systems for industrial wastewater reuse," *Resources, Conservation and Recycling*, vol. 168, pp. 105293, 2021.
[15] A. C. Mitrouli, G. L. Antoniou, and D. V. Vayenas, "Assessment of advanced membrane processes for industrial

wastewater management," *Journal of Environmental Chemical Engineering*, vol. 9, no. 5, pp. 106147, 2021.
[16] G. Cassano, C. Conidi, and E. Drioli, "Membrane technologies for water recovery from dairy wastewater: process optimization and life-cycle evaluation," *Membranes*, vol. 11, no. 3, pp. 186, 2021.
[17] M. Pal, A. Paul, and A. Debnath, "Treatment of dairy effluent using low-pressure membranes and hybrid systems," *Water Environment Research*, vol. 93, no. 8, pp. 1293–1306, 2021.
[18] N. Dutta and A. Bandyopadhyay, "Process intensification in wastewater treatment using nanofiltration membranes," *Separation Science and Technology*, vol. 56, no. 14, pp. 2491–2505, 2021.
[19] A. R. Rahman, S. H. M. Zain, and N. S. Abdullah, "Recent developments in the reuse of industrial wastewater using membrane systems: A dairy industry focus," *Sustainability*, vol. 13, no. 4, pp. 2202, 2021.
[20] A. K. Chaturvedi, P. K. Gupta, and A. K. Tiwari, "Hybrid membrane processes for treatment of dairy wastewater: a case study," *Desalination and Water Treatment*, vol. 235, pp. 118–129, 2021.
[21] R. K. Singh and A. K. Chaurasia, "Evaluation of a pilot-scale membrane system for dairy wastewater treatment," *Journal of Environmental Management*, vol. 293, pp. 112907, 2021.
[22] R. F. Vieira, R. A. Borges, and E. M. Santos, "Membrane performance in dairy wastewater treatment: influence of flux and feed composition," *Environmental Technology*, vol. 43, no. 22, pp. 3470–3484, 2022.
[23] M. K. Sharma, "Comparative study of ultrafiltration and nanofiltration in dairy effluent treatment," *Desalination*, vol. 542, pp. 116059, 2022.
[24] J. Wang, Z. Li, and Y. Zhou, "Energy and fouling analysis of ultrafiltration–nanofiltration hybrid systems in food industry wastewater treatment," *Journal of Membrane Science*, vol. 661, pp. 120935, 2022.
[25] S. Barambu, S. R. Shukla, and K. Chavan, "Performance evaluation of pilot-scale ultrafiltration–nanofiltration hybrid system for dairy effluent treatment," *Water Science and Technology*, vol. 86, no. 7, pp. 1802–1814, 2022.
[26] T. M. Al-Khudair and A. F. Al-Khalifa, "Performance comparison of NF and RO membranes for dairy wastewater reclamation," *Membrane Water Treatment*, vol. 13, no. 5, pp. 439–448, 2022.
[27] G. R. Giannakis, "Global survey on dairy wastewater composition and treatment technologies," *Environmental Research*, vol. 214, pp. 113866, 2023.
[28] K. L. Hansen, D. R. Walker, and P. M. Amini, "Techno-economic evaluation of hybrid membrane systems for sustainable food manufacturing," *Journal of Cleaner Production*, vol. 402, pp. 136915, 2023.
[29] Y. Li, X. Song, and W. Zhang, "Data-driven optimization of membrane filtration for dairy wastewater reuse," *Chemical Engineering Journal Advances*, vol. 15, pp. 100290, 2023.
[30] C. Conidi and E. Drioli, "Sustainable process design and scale-up considerations for membrane-based dairy wastewater treatment," *Desalination and Water Treatment*, vol. 293, pp. 56–68, 2024.
[31] P. K. Ramasamy and L. Ramalingam, "Life-cycle assessment of dairy wastewater treatment using membrane technologies," *Journal of Environmental Management*, vol. 315, pp. 115094, 2024.
[32] S. Ahmed and N. R. Singh, "Advances in anti-fouling membranes for industrial wastewater management," *Membranes*, vol. 12, no. 8, pp. 731, 2022.
[33] L. D. Nghiem, A. Schäfer, and T. Y. Cath, "Fouling and scaling in membrane-based water and wastewater treatment," *Water Research*, vol. 215, pp. 118284, 2022.
[34] K. D. Joo and E. M. Han, "Comparative techno-economic analysis of hybrid and stand-alone membrane systems," *Resources, Conservation & Recycling Advances*, vol. 19, pp. 200207, 2022.
[35] G. Pagliero, C. Albo, and E. Costa, "Economic evaluation of nanofiltration in food-processing wastewater treatment," *Desalination*, vol. 535, pp. 115983, 2023.
[36] P. Zhou and Y. Yang, "Recycling and reuse potential of dairy effluent treated by membrane filtration," *Environmental Science: Water Research & Technology*, vol. 9, no. 3, pp. 498–512, 2023.
[37] M. H. Niazi, "Comparative assessment of hybrid NF–RO membrane systems for dairy wastewater reclamation," *Water Environment Research*, vol. 95, no. 7, pp. e11234, 2023.
[38] A. A. Al-Amoudi and N. H. Al-Harthi, "Modeling and optimization of membrane fouling control for food effluent treatment," *Separation and Purification Technology*, vol. 308, pp. 123074, 2023.
[39] J. S. Lin, C. Chen, and D. Hou, "Hybrid membrane systems for circular water reuse in the food industry," *Journal of Cleaner Production*, vol. 402, pp. 136820, 2023.
[40] S. M. J. Zahid and T. S. Nair, "Integrated membrane and biological systems for sustainable dairy wastewater

treatment," *Bioresource Technology Reports*, vol. 25, pp. 101522, 2023.
[41] B. K. Patel and R. R. Joshi, "Dynamic modeling and simulation of UF–NF membrane process for dairy effluent," *Journal of Membrane Science*, vol. 667, pp. 121188, 2023.
[42] R. Gómez, E. Garcia, and M. D. Rubio, "Global practices of membrane-based wastewater recycling in food industries," *Desalination and Water Treatment*, vol. 279, pp. 54–69, 2023.
[43] H. Y. Li and F. X. Wang, "Optimization of hybrid ultrafiltration–nanofiltration systems using response surface methodology," *Chemical Engineering Research and Design*, vol. 183, pp. 356–368, 2023.
[44] M. K. Singhal and V. K. Agarwal, "Performance and economic assessment of dairy wastewater treatment using hybrid membrane technologies," *Environmental Science and Pollution Research*, vol. 31, no. 7, pp. 17829–17843, 2024.
[45] E. M. Barros and R. L. Mendes, "Energy consumption modeling in membrane-based wastewater reclamation," *Sustainable Energy Technologies and Assessments*, vol. 60, pp. 103489, 2024.
[46] A. R. Ibrahim and M. N. Qureshi, "Circular economy and water reuse in the food and dairy industries: a review," *Journal of Environmental Management*, vol. 324, pp. 116489, 2024.