PolyCera®

Advancing Industrial Water and Wastewater Treatment with Ultrafiltration Membranes Designed for Reduced Pretreatment

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ABSTRACT

PolyCera® ultrafiltration membranes combine ceramic-grade durability with polymeric cost efficiency, reducing pretreatment and lifecycle costs for industrial water/wastewater treatment. The nanostructured hydrophilic/oleophobic membrane material tolerates extreme conditions (pH 0-14, 90 °C, 3% oil). Open-channel monolithic modules resist clogging with 5 % suspended solids at high crossflow. Field-proven in 90+ MGD projects, including thermal power plant ZLD, lithium extraction, mining wastewater reuse, and oily produced water treatment, these membranes deliver consistent CAPEX/OPEX reductions versus conventional technologies.

INTRODUCTION

WATER SCARCITY AND THE NEED FOR ADVANCED TREATMENT – Clean, fresh water is essential to support human life, food and energy production, industrial processes and the natural environment. Traditional fresh water resources are become increasingly over-stressed and polluted, and hence, we will rely on non-traditional – difficult to treat – water sources going forward. Membrane filtration is a key to a more sustainable water future because it enables both traditional and non-traditional waters to be purified for beneficial use/reuse.

MEMBRANE FILTRATION – Herein, the term "membrane filtration" refers to microfiltration (MF) and ultrafiltration (UF), which are porous barrier materials with pores between about 10 and 100 nm designed to selectively separate particulate substances from water based on the relative size of particles and membrane pores (Fig. 1). Nanofiltration and reverse osmosis membranes are non-porous, typically selected for removing organic molecules, metals, minerals and salts from water. Membrane filtration offers an absolute barrier for removing particles larger than the membrane pore size, which includes virus, bacteria and protozoan microorganisms as well as abiotic suspended solids (clays, silt and mineral precipitates).

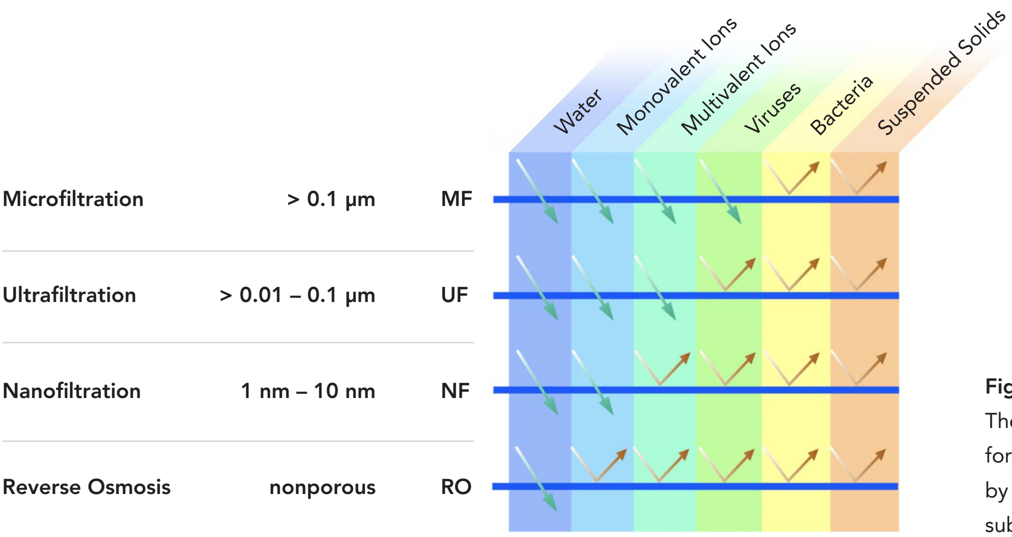


Figure 1:
The membrane filtration spectrum showing all forms of pressure-driven membrane processes by pore size, typical designation and classes of substances removed.

State of the art membrane technologies include ceramic, metallic, and polymeric membranes. Ceramic and metallic membranes are hydrophilic, can be operated at higher fluxes than polymeric membranes, withstand higher operating pressures and temperatures, have longer membrane lifetimes, and are more resistant to steam and chemical cleaning. Ceramics generally operate over a wide pH window (1 - 13). Sintered metallic membranes are common in many process microfiltration applications. These membranes are usually susceptible to corrosion in acids. Ceramic and metallic membranes are more expensive than polymeric membranes and generally lead to a larger system footprint. Commercial polymeric membranes are typically made out of polyacrylonitrile (PAN), polyvinylidene fluoride (PVDF), polyethersulfone (PES), and cellulose acetate (CA) or polytetrafluoroethylene (PTFE). These commodity polymer membrane materials are generally less hydrophilic than ceramic or metallic membranes, have lower chemical and thermal stability, and operate within narrower pH windows. These membranes are prone to fouling by organic matter and must be cleaned frequently. Ceramic membranes can be cleaned using steam, caustics, acids, and bleach, whereas state of the art polymeric UF membranes are degraded by such harsh cleaning methods, and, thus, cannot maintain their performance over acceptable operating lifetimes in many process applications.

MEMBRANE FOULING – Membrane fouling describes the loss of permeability due to accumulation of feed solids on or within a membrane's pores. Particles, bacteria, oil and organics in water foul membranes, which leads to increased back-washing, cleaning, downtime and operating cost along with decreased throughput and membrane useful life (Fig. 2). The biggest cost driver for MF/UF membranes is the fouling propensity of an influent water; generally, the sustainable flux decreases with feed suspended solids (the primary fouling materials). Lower flux increases capital cost due to applying more membrane area. Also, higher feed solids require more frequent backwash and cleaning, which means the filtration system is not filtering forward and, even worse, back-washing effectively amounts to filtering the water twice and throwing it out. In fact, back-washing is the most expensive aspect of MF/UF membranes – reducing overall water recovery and increasing process down-time.

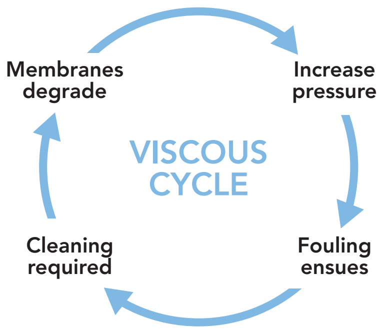


Figure 2:
Membrane Fouling Vicious Cycle

MEMBRANE FOULING PREVENTION –
Pretreatment – Membrane pretreatment refers to the treatment unit operations to remove or reduce substances in feed water that can cause membrane fouling. Typical membrane pretreatment includes chemical coagulation and flocculation, floatation, sedimentation, clarification, sand filtration, multi-media filtration, etc. Those pretreatment operations require large footprint and high labor intensity. They often need chemical dosing with low automation levels and complex operation, and high capital investment and maintenance costs. Moreover, inefficiencies or failures in pretreatment can significantly impact membrane system performance

Membrane Materials – Generally, more hydrophilic membrane materials tend to be more resistant to fouling, which translates into slower loss of permeability during forward filtration and more complete recovery upon backwash or cleaning. However, the first trade-off is that more hydrophilic polymers tend to be less robust, and hence, have shorter useful lives and when they inevitably foul operators are limited in the type and concentration of cleaning agents that can be applied. So, cleaning can be difficult. In contrast, more robust hydrophobic polymers are reasonably long lasting and can be cleaned with harsh chemistries, but their hydrophobicity lends itself to more rapid permeability loss and incomplete recovery upon backwash and cleaning. Finally, ceramics are the ideal combination of hydrophilic and robust, but they cost 10-20 times more (per unit area of membrane). Hence, they have achieved limited market share due to the high capital investment and are only used when no other options are available.

BRIDGING THE TECHNOLOGY GAP WITH ADVANCED MEMBRANES
A membrane material that has the complementary robustness and hydrophilicity of ceramics along with the economics of polymeric membranes is a long sought after innovation. Derived from novel nano-structured polymeric materials traditionally developed as organic metal polymers, this advanced membrane products exhibit ceramic-like stability and hydrophilicity, while retaining the ease of manufacturing, high packing density and favorable economics of commodity polymeric membranes. These materials have exceptional electronic properties, which lend to their superhydrophilicity, oleophobicity, as well as their adaptability to acid and base environments. These membranes are four to 5-fold less expensive than ceramics and can be produced in high packing density modules (with a footprint being up to 10-fold smaller than ceramics). These membranes offer lower cost, footprint, and energy demand, which are critical for water treatment systems and process separation applications.

HYDROPHILICITY AND FOULING RESISTANCE – One can quantify a material's "hydrophilicity" from the "free energy of cohesion" (ΔG_{131}) and one can quantify two materials' propensities to stick to one another, i.e., "fouling propensity," in an aqueous media from the "free energy of adhesion" (ΔG_{132}). A positive ΔG_{131} indicates a hydrophilic material and a negative ΔG131 indicates a hydrophobic material. Meanwhile, a positive ΔG_{132} indicates two materials that resist adhesion (slow fouling and ease of cleaning), and a negative ΔG_{132} indicates two materials that are prone to strong adhesion (fast fouling and difficulty cleaning). As shown in Fig. 3, the presenting advanced membrane material exhibits hydrophilic properties, while maintains fouling resistance to most of organic, microbial and inorganic fouling materials at a molecular level.

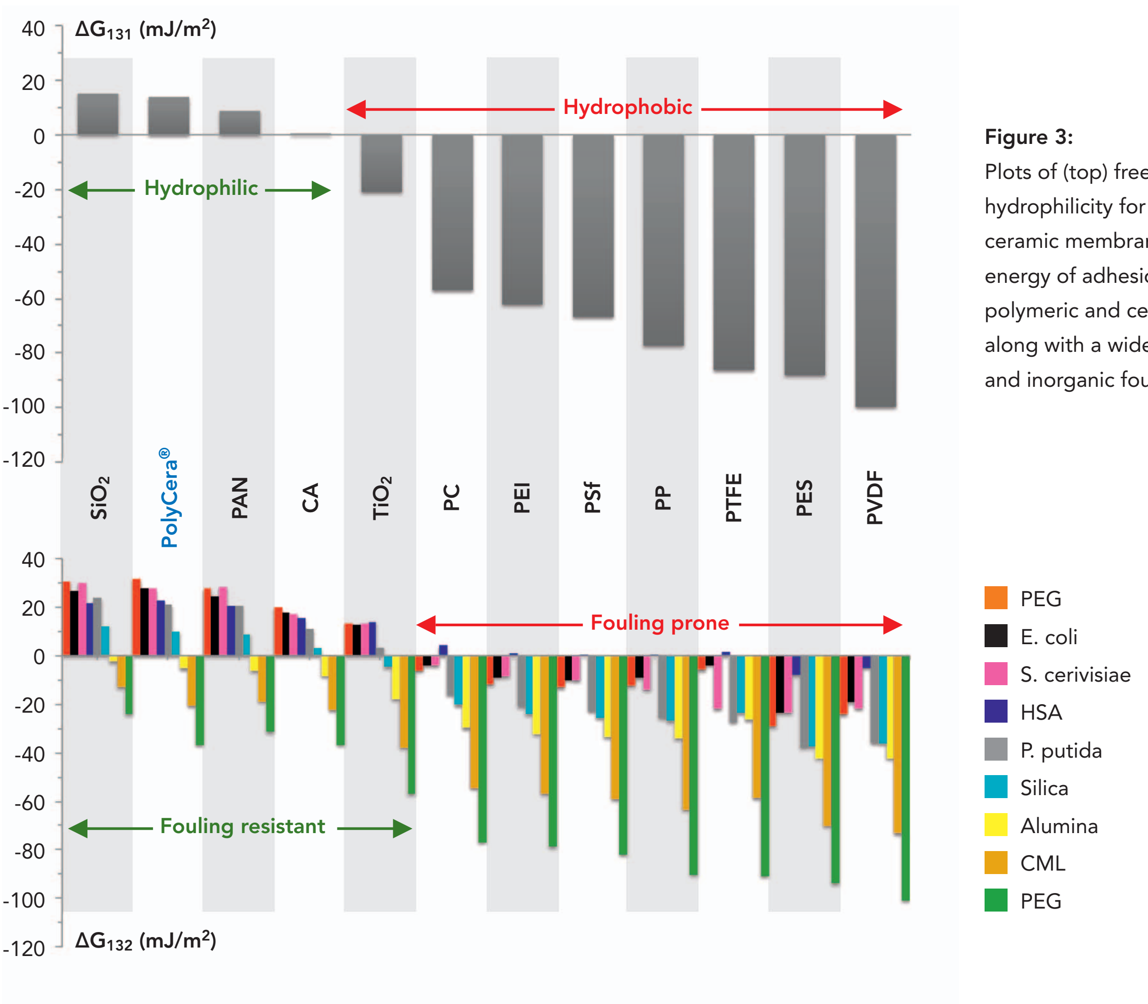
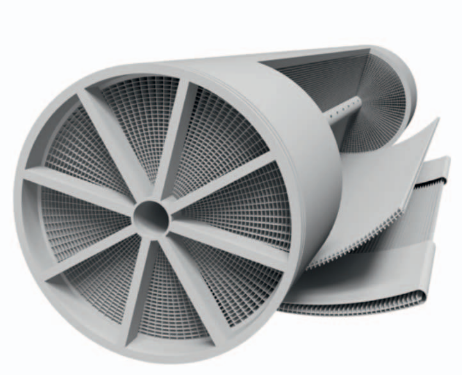


Figure 3:
Plots of (top) free energy of cohesion or hydrophilicity for common polymeric and ceramic membrane materials and (bottom) free energy of adhesion or fouling propensity for polymeric and ceramic membrane materials along with a wide range of organic, microbial and inorganic fouling materials.

OPEN CHANNEL ELEMENT DESIGN – Traditional polymeric UF modules, hollow-fiber or spiral-wound elements, employ sub-millimeter feed channels that were optimized for relatively clean waters. When total suspended solids (TSS) rise above a few tens of mg/L, particles rapidly bridge these narrow passages, creating local dead zones and steep pressure-drop increases. At the same time, the laminar, low-shear flow regime ($< Re \approx 2 \times 10^4$) promotes cohesive cake layers, and the first centimeters of the channel bear most of the solids loading, accelerating front-end fouling and fiber or spacer damage. To keep such modules operating on high-solids feeds, pretreatment processes are required, which increase the costs. The presenting advanced UF membrane features open-channel or monolith membrane element design (Fig.4). This design enlarges the feed channel from sub-millimeter gaps to multi-millimeter bores (1 – 3 mm), as a result, particles cannot bridge across the channel, while the pressure drop stays modest. For example, in 8040 spiral wound elements with 40 mil (~ 1mm) open channel, the pressure drop from feed side to concentrate side does not exceed 1 bar when the cross-flow rate is 25 m3/h (~100 GPM). The wider hydraulic path lets the modules accept feeds containing hundreds to thousands mg/L TSS or several percent free oil with minimal pretreatment.



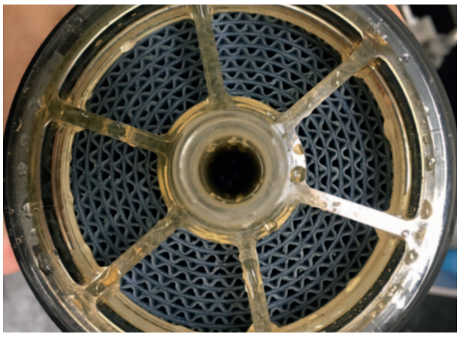
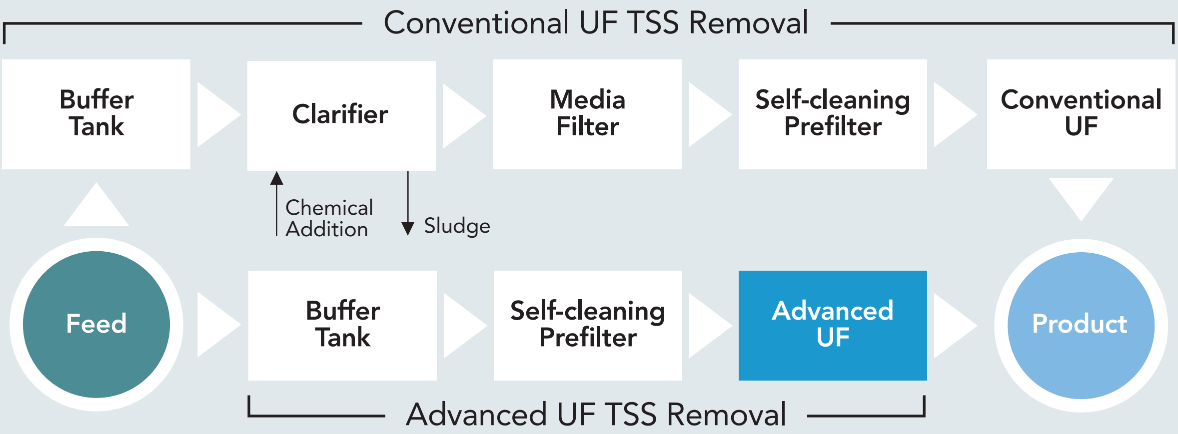


Figure 4:
Open Channel Feed Spacer Design of Spiral Wound Monolith Element

"SHORT PROCESS" FOR TSS REMOVAL – With hydrophilic and fouling resistant membrane material and backwashable open channel hydraulic module design, the advanced membrane presented in this paper offers insights to the industry about how to design membrane and system to treat industrial wastewater with reduced pretreatment. Comparing with conventional UF TSS removal process, sedimentation, clarifier, coarse and fine filter are no longer required with the advanced membranes with above features (Fig. 5). Field applications have demonstrated the effectiveness of these "short process" for TSS removal as illustrated in the case studied presented in this paper.

Figure 5:
Conventional vs. Advanced UF TSS Removal Process



CASE STUDIES

CASE 1: THERMAL POWER PLANT COOLING TOWER BLOWDOWN REUSE – Power plants face increasing pressure to reduce wastewater discharge while maintaining efficient operation. In high salinity and hardness environments (Table 1), conventional treatment methods often fall short due to scaling, membrane fouling, or high chemical demand. As a result, chemical softening is usually required in the process to reduce the scaling in reverse osmosis (RO) process. UF is typically used to remove suspended solids generated in chemical softening process prior to RO operation. However, due to low resistant to TSS of traditional UF membranes, extensive pretreatment processes are mandatory.

Parameter	Unit	Data
Temperature	°C	0 – 90
pH		7.4 – 8.5
TSS	mg/L	< 10
Turbidity	NTU	< 100
COD	mg/L	< 50
BOD	mg/L	< 20
E.coli	CFU/mL	< 2000
TDS	mg/L	< 4000
Hardness	as $CaCO_3$, mg/L	< 1500
Alkalinity	as $CaCO_3$, mg/L	< 1000
Iron	mg/L	< 5
Manganese	mg/L	< 10
Silica	as SiO_2, mg/L	< 20

Table 1:
Water Quality of Cooling Tower Blowdown

A 300 m^3/h (~ 1.9 MGD) cooling tower blowdown reuse project for a power plant employes liquid solid fluidized bed crystallization granulation for softening and UF membrane system as pretreatment for RO process. The turbidity of the outlet of crystallization granulation reactor is in the range of 10 to 300 NTU. As a result, pretreatment like clarifier and multi-media filter is required for traditional UF membrane system. As shown in Fig. 6, process utilizing presenting advanced UF system takes outlet directly from crystallization granulation reactor without any pretreatment due to its high tolerance to TSS and fouling.

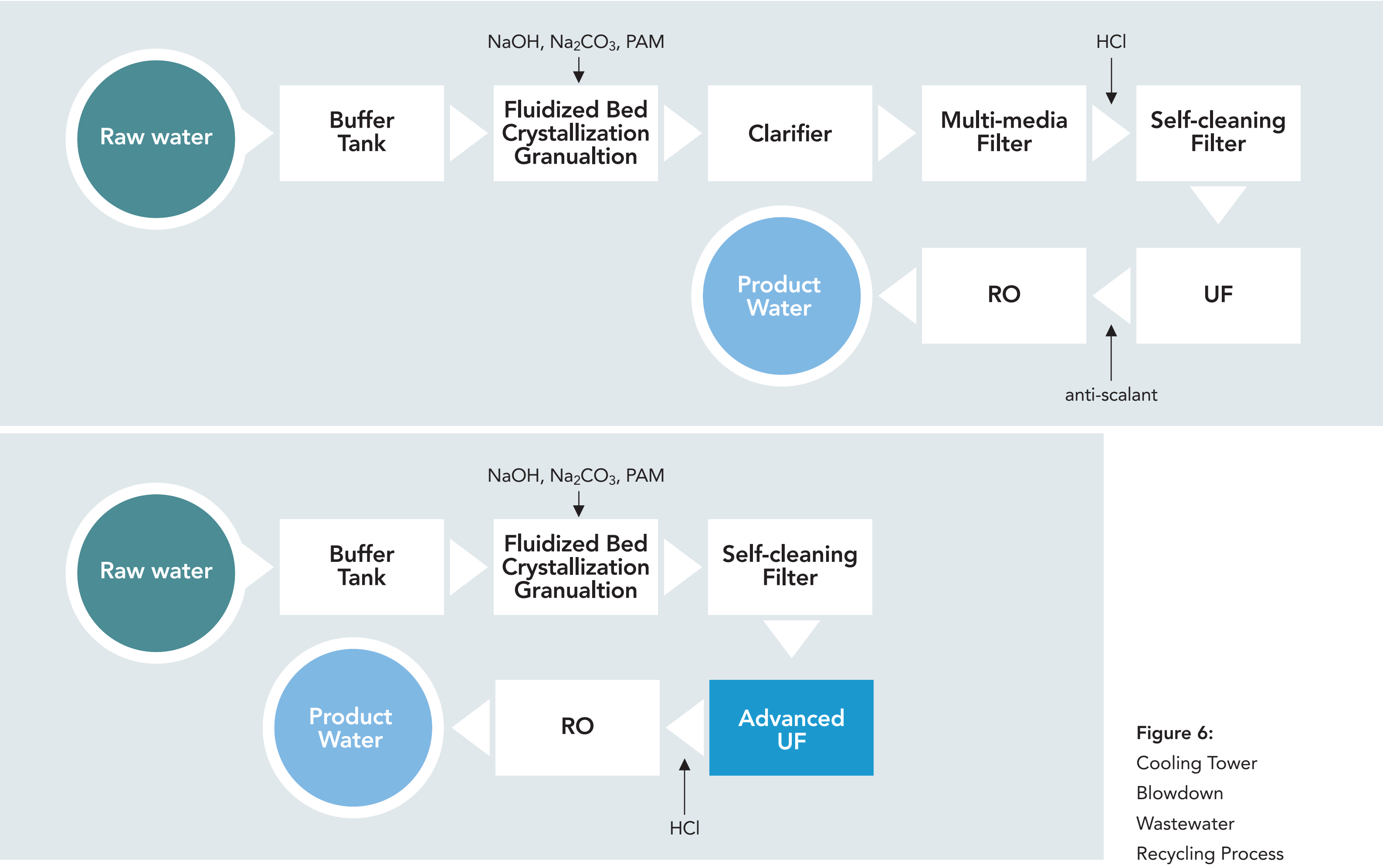


Figure 6: Cooling Tower Blowdown Wastewater Recycling Process

Figure 7: Advanced UF Membrane System in Case Study 1

The advanced UF system includes three parallel trains (Fig. 7) and operates in cross-flow single-pass mode. The operational recovery is set at 90 %, while discharging 10 % concentrate stream. Backwash with UF filtrate is employed to migrate membrane fouling. Membrane design flux is 80 LMH (~ 50 GFD), which is about two times higher than traditional UF membrane with extensive pretreatment. The backwash frequency is once every 30 minutes. UF CIP (Clean in place) frequency is larger than 30 days. Other design parameters are summarized in Table 2.

Table 2: UF System Design Parameters in Case Study 1

Parameter	Specification	Remarks
System configuration	3 parallel trains	Independent operation capability
Design capacity	100 m^3/h per train	Total output: 300 m^3/h
Membrane characteristics		
Pore size	20 nm	
Design flux	80 LMH	
Pressure parameters		
Design inlet pressure	4.0 bar	Maximum allowable
Operating pressure range	1.5 – 2.5 bar	Actual working conditions
Performance		
Permeate recovery rate	>90%	Water utilization efficiency
Filtration mode	Cross-flow single-pass	Fouling mitigation
Operational cycle		
Filtration duration	30 minutes	Between backwashes
Backwash characteristics		
Duration	90 seconds	
Method	Filtrate-only (no air scouring)	Simplified operation
Maximum pressure	<1.7 bar	Safety threshold
Flux	150 LMH	Cleaning intensity

Fig.8 shows the operational flow rate and filtrate turbidity of the system at its initial commissioning (2023) and most recent months (June and July 2025). After The system constantly operated at ~90 % recovery and produces filtrate water with turbidity less than 0.2 NTU and SDI less than 3 satisfying RO system operation.

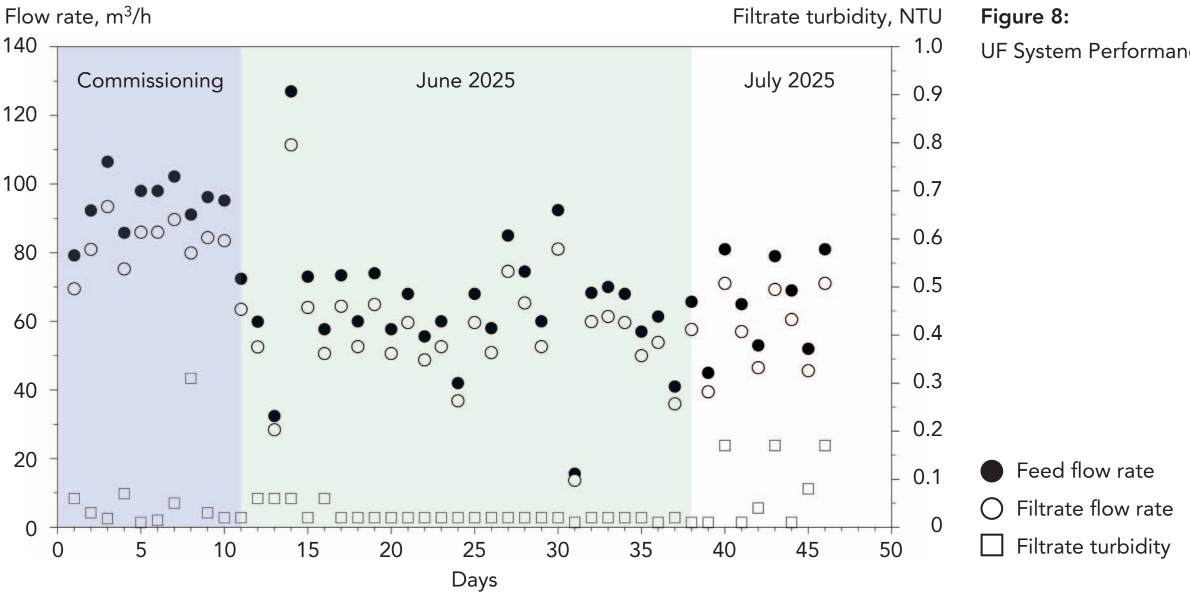


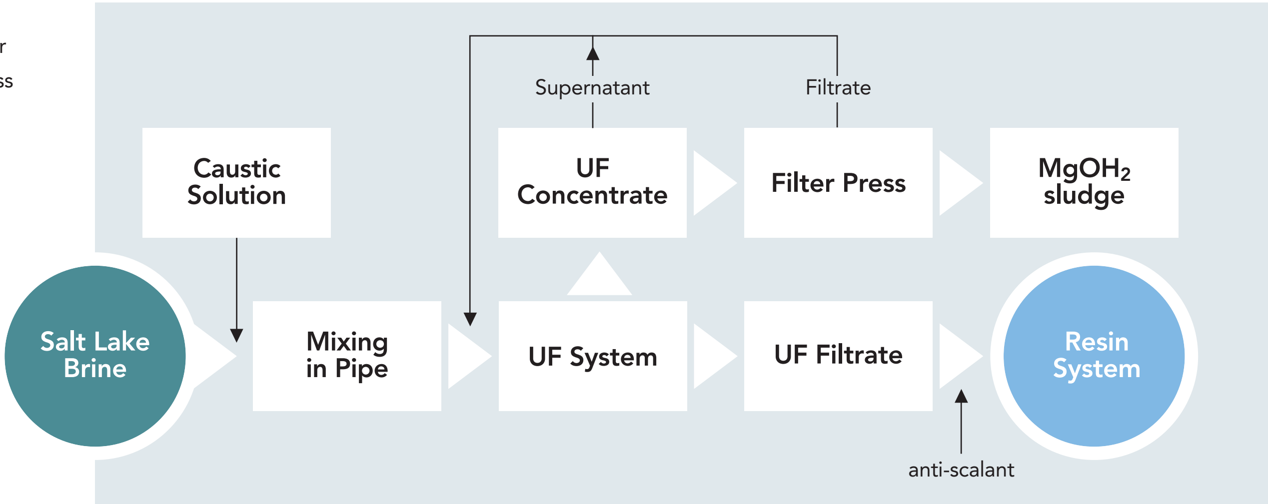
Figure 8:
UF System Performance Data for Case Study 1

The crystallized solid-liquid effluent maintains stable, high-quality feed for the advanced UF membrane system. The presenting advanced UF membrane's broad pH tolerance range (1 – 13.5) allows for effective post-treatment pH adjustment through acid dosing, efficiently retaining alkaline precipitate particles from the solid-liquid separation effluent while ensuring easy cleaning. Importantly, this pH adjustment doesn't cause redissolution of alkaline particles into the feedwater, thus preventing subsequent increases in hardness ion concentration in the final effluent.

CASE 2: LITHIUM EXTRACTION – a two phases 4,200 m³/h (1st phase: 1,900 m³/h, ~ 12 MGD; 2nd phase: 2,300 m³/h, ~15 MGD) lithium extraction project, uses advanced membrane and absorption resin technology to extract lithium from salt lake brine, enhancing efficiency and supporting the growth of renewable energy industries. It aims to produce 60,000 tons of lithium salt annually, including 30,000 tons of industrial-grade lithium hydroxide. The project addresses the surging global demand for lithium, a critical component in energy storage and electric vehicle technologies.

Raw salt-lake brine is first dosed in-line with a caustic (NaOH) solution, and the two streams are turbulently blended in a short pipe section where the elevated pH precipitates magnesium as insoluble $MgOH_2$ solids while lithium remains in the solution. The alkaline suspension (~ 750 mg/L suspended solids) then enters directly into the presenting advanced UF system without further pretreatment (Table 3). Newly formed particulates and colloids are retained in the UF concentrate, while a clarified UF filtrate passes forward. Concentrate is dewatered in a filter press, producing a compact $MgOH_2$ rich sludge for disposal or potential reuse. The lithium in the low-turbidity UF filtrate is finally enriched by an ion-exchange resin train and washed out by an acidic (HCl) solution (Fig. 9).

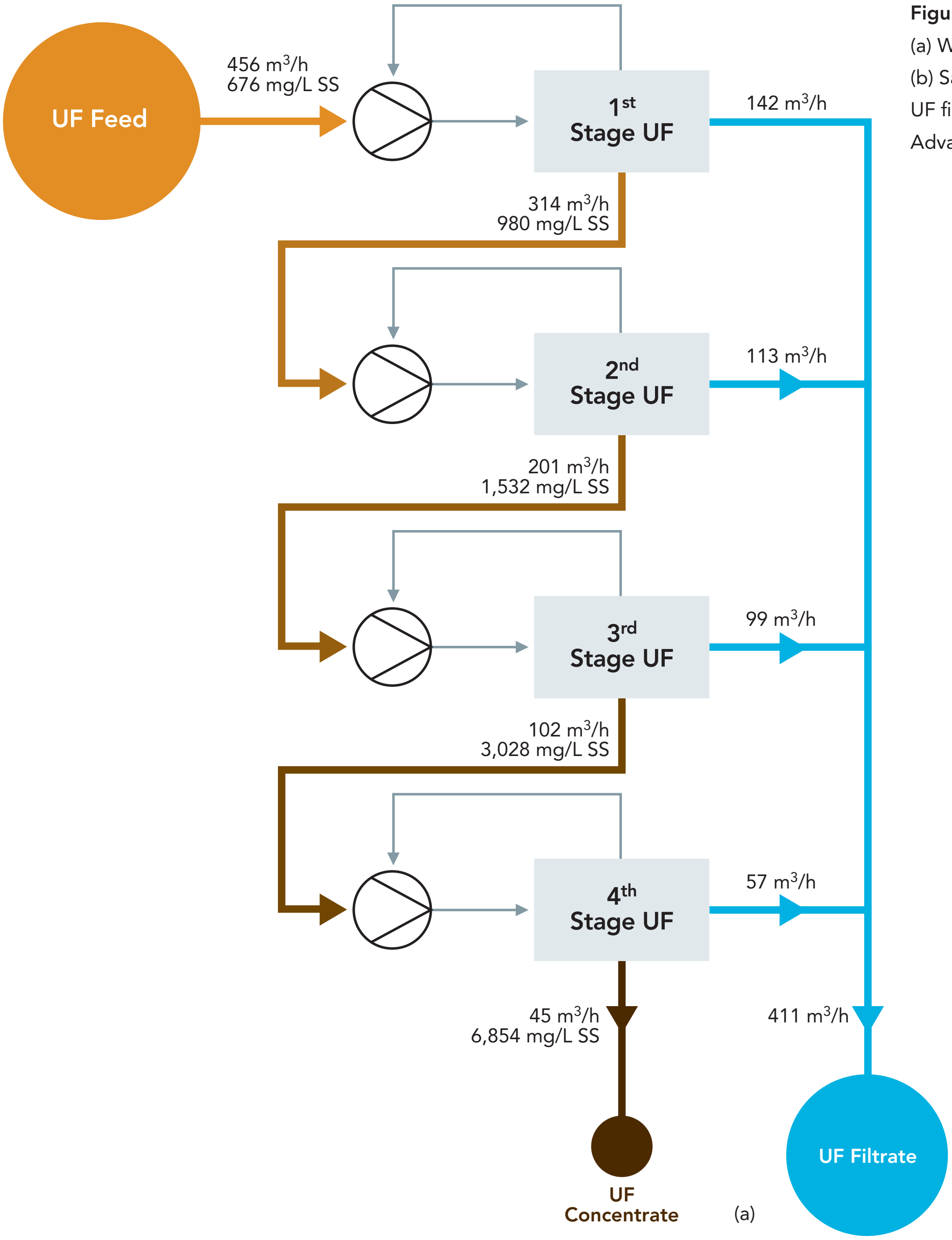
Figure 9:
Process Flow Diagram for Lithium Extraction Process



Parameter	Unit	Data
Flow rate	m3/h	4200
Na^+	mg/L	35000
$MgOH_2$, solid	mg/L	750
Ca^{2+}	mg/L	20
SO_4^{2-}	mg/L	2300
B_2O_3	mg/L	800
K^+	mg/L	2140
CO_3^{2-}	mg/L	3000
Cl^-	mg/L	55000
Li^+	mg/L	180
pH		12 – 13
Temperature	°C	< 10

Table 3:
UF System Feed Water Quality Data in Case Study 2

Currently, the ultrafiltration system operates with multiple series running in parallel, each series configured with four stages for stepwise concentration and separation (Fig. 10). The TSS in the feed is concentrated gradually in each stage to reach final concentration of ~7000 mg/L before sending to filter press. The membrane operating flux decreases from stage 1 to stage 4 purposely. This setup ensures that the ultrafiltration system can consistently produce high-quality water while maintaining stable operation.



(a)

Figure 10:
(a) Water and Mass Balance for One UF Train, (b) Sample Photo (from left to right: UF feed, UF filtrate, UF concentrate), (c) Installed Advanced UF System Photo for Case Study 2.

(b)

(c)

Parameter	Specification	Remarks
System configuration	4 parallel trains, 4 stages in each train	Independent operation capability
Design capacity	475 m³/h per train	Total output: 1900 m³/h
Membrane characteristics		
Pore size	20 nm	
Design flux	65 LMH	
Pressure parameters		
Design inlet pressure	4.0 bar	Maximum allowable
Operating pressure range	2.5 – 4 bar	Actual working conditions
Performance		
Permeate recovery rate	>90%	Water utilization efficiency
Filtration mode	Cross-flow recirculation	Fouling mitigation
Operational cycle		
Filtration duration	20-30 minutes	Between backwashes
Backwash characteristics		
Duration	90 seconds	
Method	Filtrate-only (no air scouring)	Simplified operation
Maximum pressure	<1.7 bar	Safety threshold
Flux	120 LMH	Cleaning intensity

Table 4: UF System Design Parameters in 1st Phase of Case Study 2

Fig. 11 summarized operation data observed by the authors (membrane supplier) from 8 days of onsite visit in May 2024. Membrane flux remained around 65 LMH while applied pressure less than 4 bar (mostly less than 3 bar). This demonstrated low fouling propensity during membrane system operation, with effective recovery via backwash and acid cleaning.

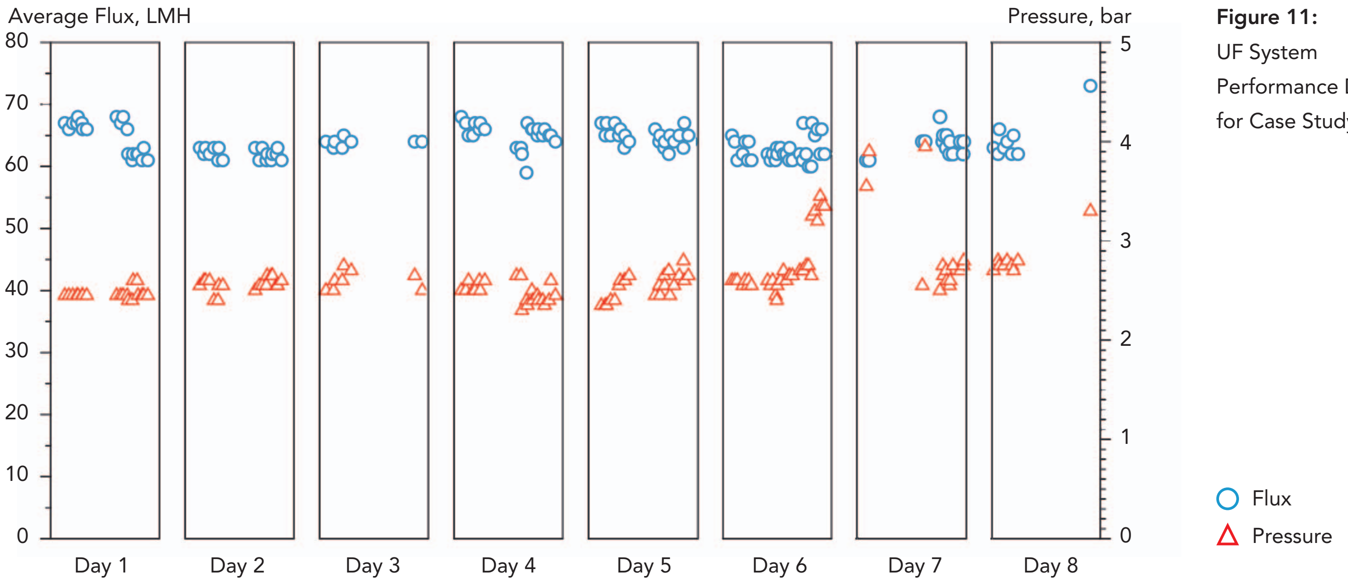


Figure 11: UF System Performance Data for Case Study 2

CASE 3: COAL MINE WASTEWATER – Traditional underground treatment of coal mine water primarily relies on magnetic coagulation and sand-enhanced coagulation processes to remove suspended solids, reduce turbidity, and partially eliminate oils and organic matter (Fig.12). Due to challenges in chemical dosing, such as high labor intensity, low automation levels, complex operation, and high maintenance costs, these methods are gradually being phased out.

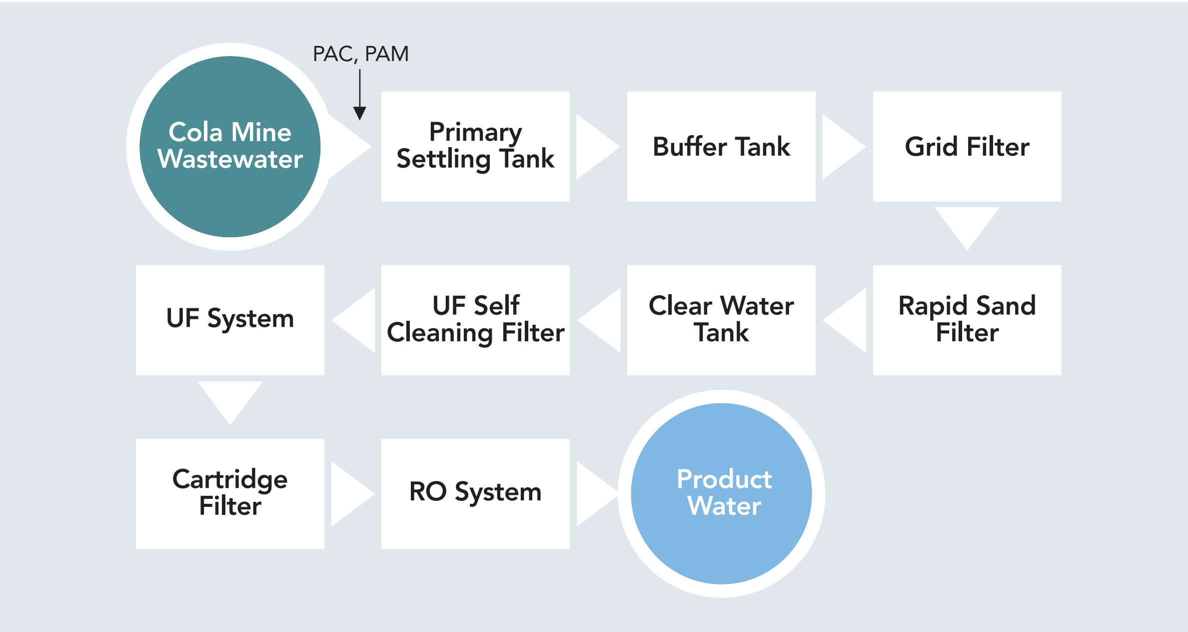


Figure 12: Traditional Coal Mine Wastewater Treatment Process

A coal mine wastewater reclamation project, featuring the presenting advanced UF membrane with a processing capacity of 200 m³/h (~1.3 MGD), plays a vital role in delivering consistent water production and providing dependable high quality water for coal mining operations. The reclaimed water is used for various purposes, improving surface water resource management in a region heavily reliant on coal mining activities. The project emphasizes environmental sustainability by reducing water waste and promoting efficient resource use. With advanced UF membrane, the system can replace six original process units: grid filter, rapid sand filter, clear water tank, traditional PVDF membrane ultrafiltration system, air scouring system, and chemical cleaning system. This optimization reduces 9 sets of rotating equipment, significantly simplifies operation and maintenance, and achieves notable space savings (Fig. 13). The feed water quality data and system design parameters are summarized in Table 5 and 6.

Parameter	Value	Unit
pH	7.5 – 8.3	
Temperature	20 – 30	°C
BOD5	≤ 300	mg/L
COD	≤ 1500	mg/L
Carbonate	≤ 500	mg/L as $CaCO_3$
Chloride	≤ 2000	mg/L
Sulfate	≤ 4000	mg/L
Calcium	≤ 650	mg/L
Magnesium	≤ 30	mg/L
Manganese	≤ 3	mg/L
Iron	≤ 20	mg/L
Alkalinity	≤ 450	mg/L as $CaCO_3$
Silica	≤ 40	mg/L as SiO_2
E.coli	≤ 50	CFU/100mL
TSS	≤ 1000	mg/L
TDS	≤ 10000	mg/L

Table 5:
UF System Feed Water Quality Data in Case Study 2

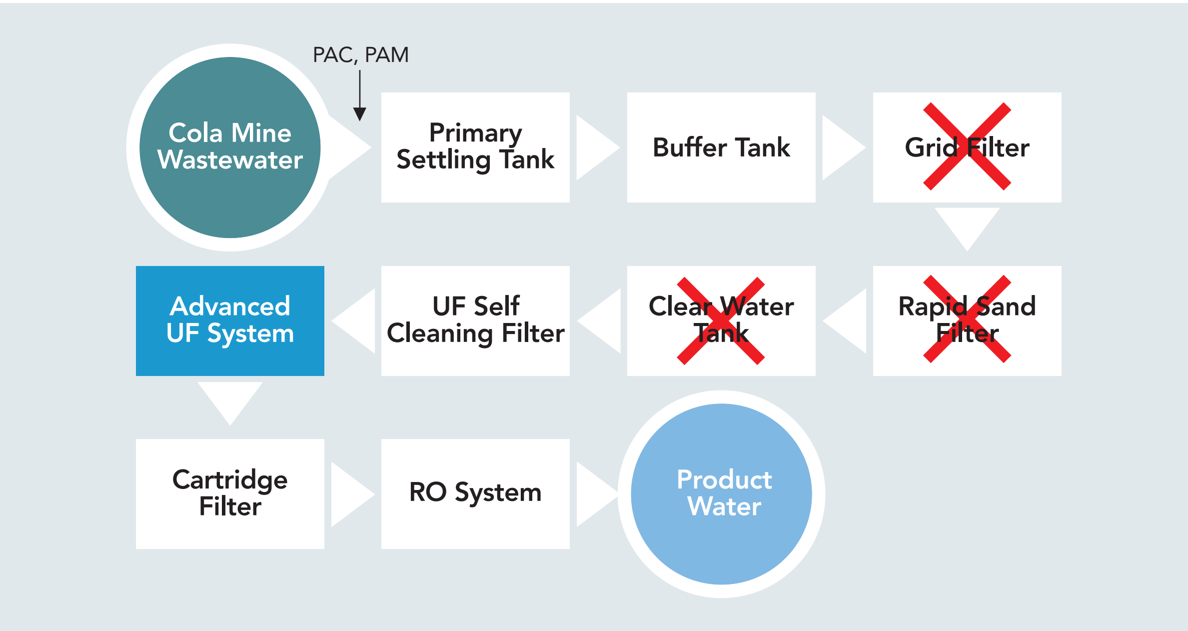


Figure 13:
Coal Mine Wastewater Treatment Process

Installed System with Advanced UF Membrane

Table 6: UF System Design Parameters in Case Study 3

Parameter	Specification	Remarks
System configuration	2 parallel trains	Independent operation capability
Design capacity	100 m³/h per train	Total output: 200 m³/h
Membrane characteristics		
Pore size	20 nm	
Design flux	71 LMH	
Operating flux	80 LMH	12.6 % above design
Pressure parameters		
Design inlet pressure	4.0 bar	Maximum allowable
Operating pressure range	1.3-1.6 bar	Actual working conditions
Performance		
Permeate recovery rate	>80 %	Water utilization efficiency
Filtration mode	Cross-flow recirculation	Fouling mitigation
Operational cycle		
Filtration duration	20-30 minutes	Between backwashes
Backwash characteristics		
Duration	90 seconds	
Method	Filtrate-only (no air scouring)	Simplified operation
Maximum pressure	<1.7 bar	Safety threshold
Flux	150 LMH	Cleaning intensity

The membrane system ensures high recovery rates (over 80%) and stable water production (Fig. 14). The UF treated water quality meets design requirements as follows: turbidity ≤ 0.1 NTU and suspended solids < 1 mg/L, which is suitable for downstream RO system.

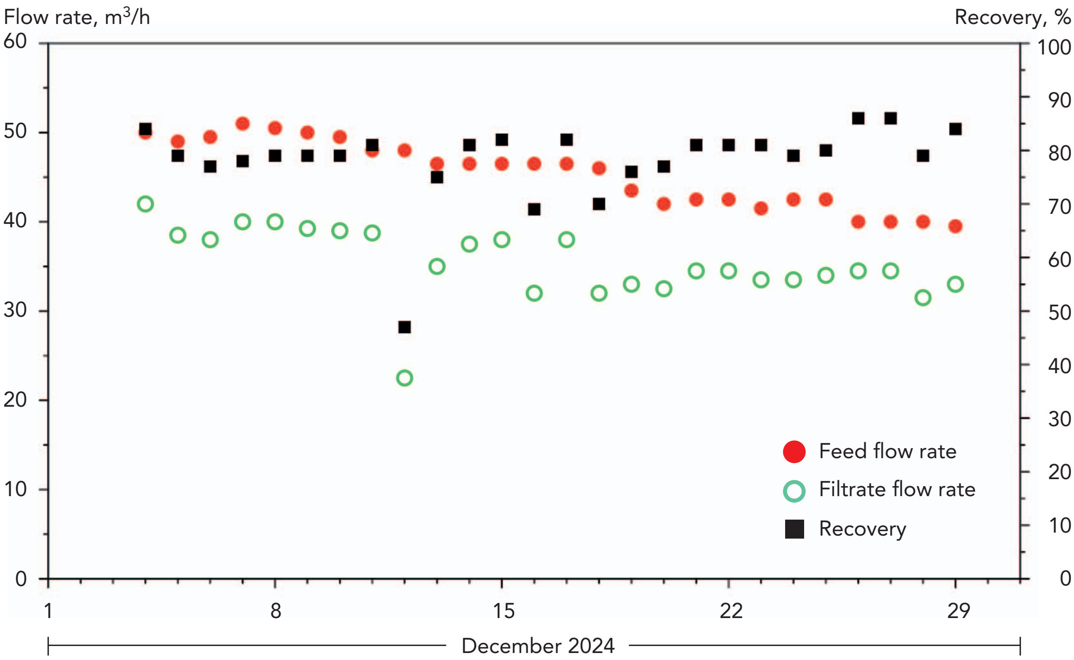


Figure 14:
UF System Performance Data for Case Study 3

After the implementation of the upgraded and expanded project, significant improvements are expected in energy efficiency, water conservation, operational cost savings, and water quality enhancement. Compared to the existing process technology, the energy consumption for lifting water to the surface is reduced by approximately 5.31 kWh per ton of water, resulting in annual electricity savings of about 8.762 million kWh. Additionally, surface treatment energy consumption is reduced by 0.9 million kWh/year, and energy use for reinjecting treated water back underground is reduced by 1.6 million kWh/year, leading to total annual energy savings of approximately 9.13 million kWh. The total annual operational cost savings amount to approximately US$1.31 million.

CONCLUSION

This work demonstrates that advanced ultrafiltration technology—combining intrinsically hydrophilic, fouling-resistant polymer chemistry with back-washable, open-channel monolith modules—can treat industrial wastewaters containing elevated suspended solids with little or no conventional pretreatment. The millimeter-scale flow passages suppress bridging and pressure-drop build-up, allowing turbulent cross-flow at high flux while maintaining long-term hydraulic stability. By eliminating fine screening, clarifiers, media filter and extensive chemical conditioning, the design cuts both capital and operating expenditures, making UF a more economical and practicable option for industrial high suspended solids removal applications.

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