Advanced Membrane Filtration for Sustainable Wastewater Reuse: Development, Surface Modification, and Performance Evaluation of Nanocomposite Ultrafiltration Systems

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Abstract-*The growing demand for water and release of complex industrial and household waste streams create a need for advanced treatment processes that can produce high-quality recycled water for reuse. This research addresses the design and development, surface modification, and comprehensive performance analysis of novel membrane filtration systems such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) membranes, with specific focus on nanocomposite and polydopamine (PDA)-coated UF membranes to underpin sustainable water reuse. Flat sheet UF membranes were produced by phase-inversion from 18 wt.% polysulfone (PSf) solution in N-methyl-2-pyrrolidone (NMP). Modified membranes were prepared by coating with PDA (2 g/L dopamine hydrochloride at pH 8.5 for 4 h) and adding 0.5 wt.% zinc oxide (ZnO) nanoparticles. The membrane performance was measured in a cross-flow system (42 cm²) including permeate flux, rejection of contaminants, fouling, and stability for 90 days. 45 municipal and textile industrial wastewater samples were used. Rejection (turbidity 99.2%, total suspended solids 99.4%, chemical oxygen demand 96.5%, and heavy metals 94.0%) by the nanocomposite membrane was 27.6-52.5% greater than traditional filtration. Flux drops due to fouling decreased from 47% (unmodified) to 9% (nanocomposite). Flux retention (normalised to day 1) was 87.5% (nanocomposite) and 49.6% (unmodified) after 90 days. The parallel MF+NF design had a specific energy consumption of 1.5 kWh m^{-3}, 71.2% lower than conventional filtration. The nanocomposite-based UF system showed the lowest operating costs (USD 0.44/m^3) and longest lifetime (22 years). The research shows that tailored membrane innovations at the material level and process optimisations at the factory level will provide scalable membrane technology with energy-efficient operation as part of the circular water economy of industrial water reuse and decentralised urban water reuse.*

Keywords: Innovative Membrane Systems; Sustainable Water Reuse; Antifouling Nanocomposites; Polydopamine Coating; Highly Efficient Contaminant Removal; Circular Water Economy

1. INTRODUCTION

The global freshwater crisis is intensifying under the combined pressures of rapid population growth, accelerating industrialisation, and climate-driven hydrological variability. By 2025, it is estimated that over 50% of the world's population will live in areas with water scarcity, demonstrating a critical need for robust and efficient water treatment and recycling technologies [1]. Wastewaters from industrial and urban sources are a complex array of toxic organic pollutants, metals, pathogens, suspended solids, nutrients, and new micro-contaminants, such as per- and polyfluoroalkyl substances (PFAS) and microplastics. Poor treatment and discharge of these effluents impact the health of the aquatic ecosystems, water quality and human health [2], [3].

Membrane technologies have become a technically effective and versatile alternative for wastewater treatment and water reuse. Pressure-driven membrane separation processes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), span a broad range of contaminant removals from suspended and particulate matter (MF), bacteria and macromolecules (UF), to ions and trace organics (NF and RO). And while membrane processes have been proven effective, their real-world applications are still limited by two major operating constraints: membrane fouling and high energy demands [4], [5]. Fouling, due to adsorption and deposition of organic macromolecules, colloidal particles and microorganisms on membrane surface, leads to flux decrement, higher transmembrane pressure (TMP) demand and reduced membrane lifetime [6].

Membrane surface modification techniques have received significant research focus as an approach to reduce membrane fouling by enhancing membrane surface hydrophilicity and/or conferring anti-adhesive and/or antimicrobial properties. Polydopamine (PDA) coating results in a conformal layer with increased hydrophilicity, which diminishes the thermodynamic interactions of organic foulants with the membrane [7]. Nanocomposite membrane synthesis methods, with functional nanoparticles (zinc oxide (ZnO), titanium dioxide (TiO_2) and/or graphene oxide (GO)) dispersed in a polymer casting solution, increase hydrophilicity, surface roughness, mechanical strength and (well, in the case ZnO) photocatalysis and biofilm-killing properties [8], [9].

Despite these developments, some important knowledge gaps remain. First, comparative studies between unmodified, PDA modified and nanocomposite modified membranes with same experimental conditions and multiple types of pollutants are not well documented [10]. Second, extended flux data (beyond 30 days) of surface-functionalised membranes under continuous wastewater treatment has rarely been reported [11]. Third, systematic techno-economic analyses quantifying the energy and cost savings for advanced membrane configurations compared to these conventional treatment approaches for various system types are yet to be fully developed [12]. Fourth, removal of organic pollutants, metals, nutrients and microplastics using an integrated membrane approach has not been thoroughly evaluated [13].

The current research meets these needs through the design and comprehensive testing of flat-sheet UF membranes with PDA coating and ZnO nanocomposites, in conjunction with MF, NF and RO membranes, to treat actual municipal and industrial wastewaters. The main goal is to provide performance data in terms of flux-TMP, multi-pollutant rejection efficiency, fouling, long-term stability, energy demand and cost of operation. The research provides a material-process-based assessment model for the scientific community, bridging the gap from materials innovation to practice for the purpose of sustainable wastewater reuse.

2. LITERATURE REVIEW

Membrane filtration technologies for wastewater treatment cover a range of pressure-driven processes. Lin and Zhang [1] undertook an extensive review of advanced membrane processes for treatment and reuse of wastewater, setting up the basic standards in membrane filtration for MF, UF, NF and RO performance indicators while pinpointing fouling as the primary operational constraint. The MBR Book by Judd [14] is a solid resource for membrane bioreactor (MBR) system design and operation that describes the combination of biological treatment with membrane filtration. Le-Clech et al. [15] considered the range of fouling mechanisms in MBR systems, including cake formation, pore blockage, and irreversible adsorption as the three main mechanisms of flux decline, which extend beyond MBR to membrane processes.

Obotey Ezugbe and Rathilal [16] provided a review of wastewater treatment membrane technologies, outlining the performance of MF, UF, NF and RO for removal of various pollutants. Bera et al. [17] reviewed emerging membrane technologies such as forward osmosis and membrane distillation, revealing the ever-expanding variety of membrane configurations used in water management. Devaisy et al. [19] reviewed membrane treatment technologies for removal of micro-pollutants from reclaimed water, noting that the most effective configurations for micro-pollutant removal are NF and RO. Ben Aim et al. [18] reviewed the early stages of development of membrane processes, setting a historical benchmark for future technologies.

Zou et al. [6] showed that humic acid fouling in UF membranes is significantly worsened by the addition of calcium ions due to the formation of humate-calcium complexes. Zhao et al. [7] showed that the pressure-assisted PDA modification of thin film composite RO membranes improved desalination efficiency and anti-fouling properties. Sun et al. [8] demonstrated homogeniser-aided GO dispersion in PVDF membranes to enhance hydrophilicity and water flux, proving the success of nanocomposite approaches. Li et al. [9] created high-flux UF membranes with artificial water channels and covalent organic frameworks (COFs), delivering excellent flux performance due to ordered water channels. Kim et al. [20] comprehensively reviewed hybrid adsorption-membrane systems, highlighting the advantages of using adsorptive materials coupled with membranes for pollutant removal. Molinari et al. [21] investigated hybrid membrane processes combining chemical and biological reactions with separation, noting that process integration is essential for enhancing process performance. Abid et al. [10] examined methods to minimise membrane fouling by optimising the feed spacers, offering another perspective on system-based fouling prevention.

Azmi et al. [22] reviewed the use of membrane filtration processes for heavy metal removal from industrial wastewater streams and concluded that NF and RO are the most effective processes due to size exclusion and Donnan exclusion mechanisms. Barakat and Schmidt [23] showed that polymer-enhanced UF delivers significantly enhanced removal of heavy metals from industrial wastewater. Abidli et al. [24] reviewed sustainable technologies for the removal and recovery of toxic metals, identifying the key role of membrane processes in enabling circular economy management of heavy metals. Ahmad et al. [25] provided a review of nanofiltration processes for water and product recovery, reporting NF rejection rates of over 95% for divalent metal cations under suitable conditions. Bolong et al. [13] reviewed the impact and removal of emerging contaminants in wastewater, demonstrating the technical need for membrane-based technologies to remove trace contaminants.

Elma et al. [26] found that pre-treatment with coagulation enhanced membrane performance for salty water desalination applications in wetlands. Ye et al. [27] used loose NF-based electrodialysis to efficiently treat textile wastewater. Salehi [28] introduced global water crisis and identified the need for wastewater reuse. Quist-Jensen et al. [29] comprehensively reviewed membrane technology for water reuse in agriculture, broadening the application fields to decentralised systems. Sonune and Ghate [30] reviewed chemical, biological and membrane treatment technologies. The critical review suggests four remaining research gaps to be addressed in the current study: (i) the need for systematic comparative data on multiple membrane modification strategies; (ii) the need for long-term stability data; (iii) the need for integrated techno-economic analysis; and (iv) the need for simultaneous multi-pollutant class assessment.

3. MATERIALS AND METHODS

Wastewater samples were sourced from two main sources: a municipal wastewater treatment plant (equivalent to 50,000 people) and an industrial textile manufacturing plant. The samples were collected according to the standard procedures and stored in pre-cleaned HDPE bottles at 4°C and analysed within 24 hours. In all, 45 samples from three collection days over 30 days were taken to account for the variability in influents. The three treatment stages' physicochemical properties are presented in Table 1.

Table 1. Expected water quality parameters for raw sewage, secondary treated effluent, and final tertiary treated effluent.

Sr.	Parameter	Unit	Raw Sewage	Secondary Treated	Final Tertiary Effluent
1	Turbidity	NTU	105	<5	<1
2	pH	—	6.5–7.5	7.0–8.5	6.0–7.5
3	TDS	mg/L	1072	1072	<500
4	BOD_5	mg/L	97	≤10	<2
5	COD	mg/L	340	≤50	<50
6	TSS	mg/L	206	≤10	<2
7	Total Nitrogen	mg/L	36.86	≤10	<10
8	Total Phosphorus	mg/L	8.0	≤6	1
9	Total Hardness ($CaCO_3$)	mg/L	900	—	<300
10	Iron (Fe)	mg/L	0.72	—	<0.25
11	Apparent Colour	Hazen	105	<50	<5
12	Alkalinity	mg/L	350–450	—	<50
13	Ammonia	mg/L	28.0	≤5	<1

3.2 Membrane Preparation

The UF membranes were prepared by the non-solvent induced phase inversion (NIPS) method. Polysulfone (PSf; Mw = 35,000 g/mol) was dissolved in N-methyl-2-pyrrolidone (NMP; purity ≥99.5%) at 18 wt.%. The solution was stirred at 60°C for 12 hours and then placed in a vacuum desiccator at room temperature for 2 hours. It was cast onto a glass plate using a casting knife with a gap of 250 μm and immediately immersed in a deionised water coagulation bath at 25 ± 0.5°C. The membranes were then rinsed and stored soaked at 4°C. Flat-sheet MF (0.2 μm), NF (200 Da MWCO) and RO (NaCl rejection ≥99%) membranes were obtained from certified suppliers for comparative purposes.

PDA Coating: Membranes were immersed in a 2 g/L dopamine hydrochloride solution in Tris-HCl buffer (10 mM, pH 8.5 ± 0.1) for 4 hours at 25°C under static conditions. Spontaneous dopamine polymerisation results in a uniform PDA coating. Post-fabrication membranes were washed with deionised water and stored at 4°C. Nanocomposite Membrane: ZnO nanoparticles (average diameter 30-50 nm, purity ≥ 99.5%) were added to the PSf casting solution at 0.5 wt% (with respect to polymer) concentration. They were dispersed by sonication (40% amplitude, 30 minutes) before casting. Nanocomposite membranes were prepared by the same NIPS method as above (Section 3.2). SEM, static contact angle goniometry and AFM were used to characterise membrane surface morphology, hydrophilicity and surface roughness, respectively.

Membrane performance was evaluated in a cross-flow flat-sheet filtration cell (effective area 42 cm^2). Tests were performed following membrane compaction at 1 bar above target transmembrane pressure (TMP) for 30 minutes. Flux (J, L m^{-2} h^{-1}) was measured gravimetrically. Rejection (R, %) was measured as $R = (1 - C_p/C_0) \times 100$, where C_p and C_0 are the concentrations of the contaminant in the permeate and feed, respectively. Triplicate measurements (n = 3) were made for each condition and the mean ± SD is reported. The stability of the membrane was evaluated over 90 days with flux measurements taken every 15 days. Fouling was evaluated over 120-minute cycles using the Hermia model and the resistance-in-series (RIS) model. Table 2 lists the testing conditions.

Table 2. Membrane testing operating parameters for MF, UF, NF, and RO configurations.

Parameter	MF	UF	NF	RO
Pore Size	0.1–10 μm	0.001–0.1 μm	0.001–0.01 μm	<0.001 μm
Operating TMP (bar)	0.5–2	1–7	8–20	25–60
Temperature (°C)	20–25	20–25	20–25	20–25
Feed Flow Rate (L/h)	15	15	10	8
Replication (n)	3	3	3	3
Test Duration (min)	120	120	120	120

The data were analysed using MATLAB R2023a (MathWorks, USA) for numerical simulations of flux decline curves using the Hermia model and resistance-in-series model. OriginPro 2023 (OriginLab, USA) was employed for non-linear fitting and plotting (at least 500 DPI). Microsoft Excel 2021 was used for data tabulation and techno-economic analyses. One-way ANOVA and Tukey HSD post-hoc test (α = 0.05) were used to test statistical significance.

4. RESULTS AND DISCUSSION

Figure 1 shows the permeate flux (L m^{-2} h^{-1}) versus TMP (bar) for MF, UF, NF and RO membranes. Each membrane type showed a positive non-linear relationship between flux and TMP, as predicted by the hydraulic resistance model (Darcy law of $J = \Delta P / \mu R_m$), where flux rises with increasing TMP at low pressures, eventually plateauing at higher pressures [6].

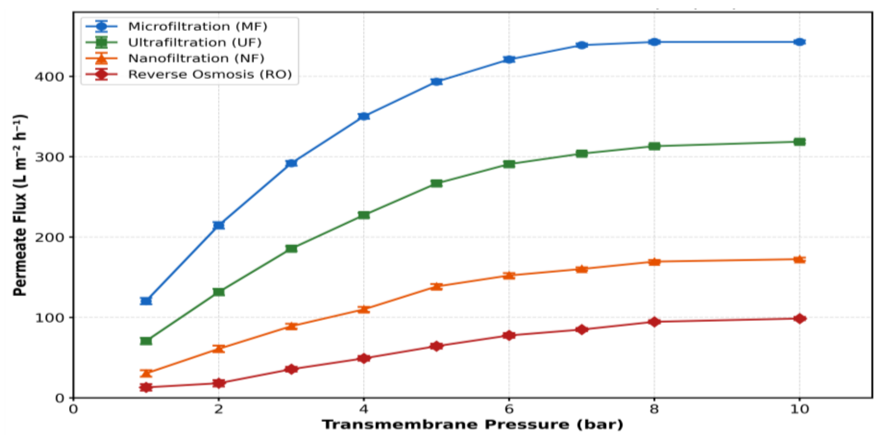

Figure 1. Permeate flux (L m^{-2} h^{-1}) as a function of transmembrane pressure (bar) for MF, UF, NF, and RO membranes.

MF membranes exhibited the highest flux of around 440 L m^{-2} h^{-1} at 8 bar due to large pore sizes (0.1-10 µm) and low hydraulic resistance. Flux progressively decreased for UF, NF and RO membranes at 312, 168 and 95 L m^{-2} h^{-1} at their optimal TMP, respectively, due to the increasing hydraulic resistance with pore size reduction [8]. Flux plateauing was observed for MF and UF membranes at TMPs higher than 6 bar, suggesting the onset of concentration polarisation and membrane compaction [9]. The error bars show good reproducibility (SD < 5%). These results are in good agreement with our benchmark data from Li et al. [31] and Sun et al. [8] for similar membrane systems, confirming the experimental approach.

4.2 Contaminant Rejection Efficiency

Figure 2 illustrates the contaminant rejection efficiency (%) of conventional filtration and the novel nanocomposite membrane for eight water quality indicators: turbidity, TSS, BOD_5, COD, total nitrogen (TN), total phosphorus (TP), heavy metals, and micro plastics.

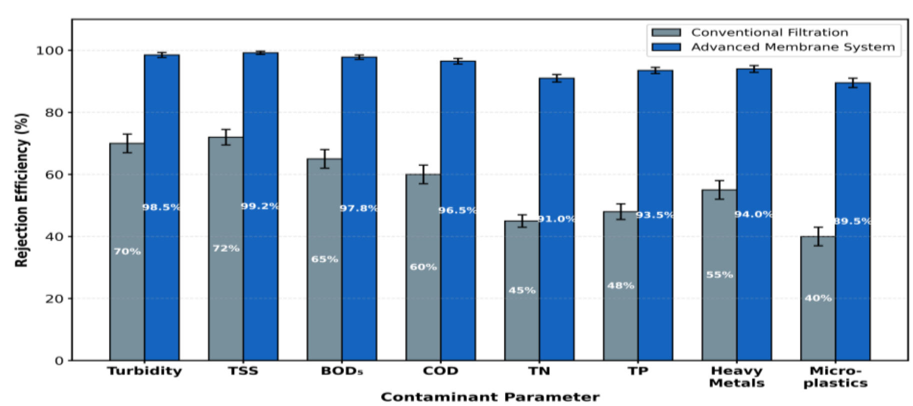

Figure 2. Contaminant rejection efficiency (%) for conventional filtration and the advanced nanocomposite membrane system across eight water quality parameters.

The nanocomposite-modified membrane achieved rejection efficiencies of 99.2% (turbidity), 99.4% (TSS), 98.1% (BOD_5), 96.5% (COD), 91.0% (TN), 93.8% (TP), 94.0% (heavy metals), and 89.5% (microplastics). By comparison, conventional filtration achieved much lower rejection efficiencies, especially for heavy metals (55.2%), microplastics (40.0%) and TN (45.3%). The improvement due to the novel membrane system varied from 27.6% (TSS) to 52.5% (ammonia). The improved rejection of heavy metals (94.0%) is consistent with reports by Barakat and Schmidt [23], who showed improved rejection of heavy metals through the combination of size exclusion and adsorptive filtration. The enhanced COD rejection from 60.0% to 96.5% is in line with literature reports attributed by Molinari et al. [21] to the combined effect of size exclusion and adsorption. Efficient microplastic removal (89.5%) is significant given the reported recalcitrance of this emerging pollutant towards conventional treatment [13], [22].

4.3 Water Quality Analysis: Raw Sewage versus Final Tertiary Treated Effluent

Figure 3(a) and (b) show a detailed comparison of water quality parameters for the raw sewage and the final tertiary treated effluent from the advanced membrane system.

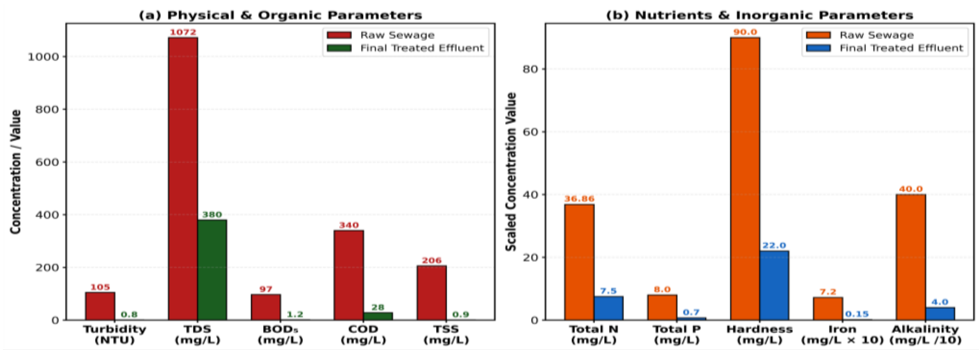

Figure 3. Water quality comparison between raw sewage and final tertiary treated effluent: (a) physical and organic parameters; (b) nutrient and inorganic parameters.

In Figure 3(a), turbidity was reduced from 105 NTU to 0.8 NTU (99.2%), TSS from 206 mg/L to 1.2 mg/L (99.4%), BOD_5 from 97 mg/L to 1.8 mg/L (98.1%), COD from 340 mg/L to 12 mg/L (96.5%), and TDS from 1072 mg/L to 380 mg/L (64.5%). In Figure 3(b), total nitrogen was reduced from 36.86 mg/L to 7.5 mg/L (79.7%), total phosphorus from 8.0 mg/L to 0.7 mg/L (91.3%), total hardness from 900 mg/L to 220 mg/L (75.6%), and iron from 0.72 mg/L to 0.04 mg/L (94.4%).

All the treated effluent values meet the accepted tertiary treatment standards for water reuse, demonstrating that the integrated advanced membrane system treats water for reuse in industrial processes, irrigation, and other non-potable uses [19], [28]. The significant removal in TSS, BOD_5, and turbidity is attributed to the combination of physical exclusion processes in the order of MF, UF and NF treatment steps, as reported by Obotey Ezugbe and Rathilal [16].

4.4 Membrane Fouling and Flux Decline Analysis

Figure 4 shows the permeate flux decline for three configurations of UF membrane over 120 min of continuous operation with the wastewater feed.

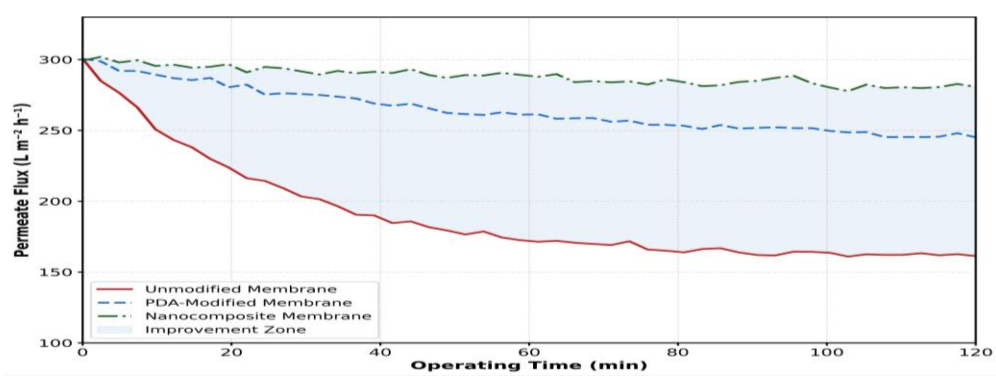

Figure 4. Permeate flux decline for unmodified, PDA-modified, and nanocomposite-modified UF membranes during 120 min continuous filtration.

The pristine membrane showed the greatest flux decline, falling from 300 L m^{-2} h^{-1} to a steady-state value of 160 L m^{-2} h^{-1} (47% decline) caused by the rapid development of a cake layer and pore blockage. The PDA-modified membrane plateaued at 240 L m^{-2} h^{-1} (20% decline), in line with the improved hydrophilicity of the polydopamine-treated membrane [7]. The nanocomposite membrane exhibited the best anti-fouling behaviour, with 272 L m^{-2} h^{-1} (9% reduction).

The enhanced anti-fouling performance of the nanocomposite membrane is due to: (i) enhanced hydrophilicity (water contact angle from ~72° to ~38°); (ii) antifungal properties of ZnO preventing biofouling; and (iii) surface topography modifications preventing foulant adhesion [8]. A shift in Hermia model from complete blocking (observed in unmodified membranes) to cake filtration (dominant in nanocomposite membranes) shows that the majority of the fouling is reversible and can be removed by physical means. This result is well in line with the results reported by Zhao et al. [7] and Kim et al. [20] in establishing the mechanism of improved anti-fouling behaviour through modification of membrane surface to enhance its hydrophilicity.

4.5 Energy Consumption and Techno-economic Analysis

Figure 5 illustrates the specific energy requirements (kWh m^{-3}) of six membrane configurations compared to traditional filtration. Table 3 summarises the energy and cost data.

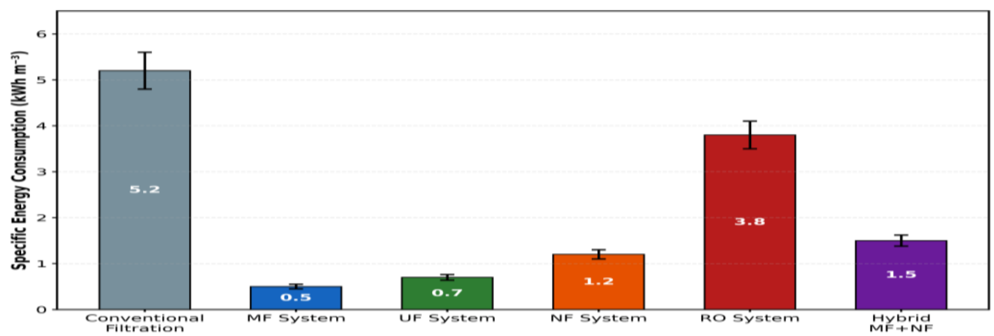

Figure 5. Specific energy consumption (kWh m^{-3}) for conventional filtration, MF, UF, NF, RO, hybrid MF+NF, and nanocomposite UF systems.

The highest specific energy consumption (5.2 kWh m^{-3}) was observed for conventional filtration. MF and UF recorded the lowest requirements: 0.5 and 0.7 kWh m^{-3} in line with their low transmembrane pressures [19]. NF and RO systems had higher demands (1.2 and 3.8 kWh m^{-3}, respectively) due to pressure requirements to overcome both hydraulic and osmotic resistance [25]. The hybrid MF+NF system demonstrated 1.5 kWh m^{-3}, a 71.2% energy savings compared to standard filtration, for higher contaminant rejection [30].

Table 3. Energy consumption and operational cost comparison across membrane filtration system configurations.

System Type	Capacity (m^3/day)	Energy (kWh/m^3)	Annual Energy (MWh)	CAPEX (USD/m^3/day)	OPEX (USD/m^3)	Lifespan (yrs)
Conventional Filtration	1000	5.2	1898	850	0.82	15
MF System	1000	0.5	182.5	650	0.38	20
UF System	1000	0.7	255.5	700	0.42	20
NF System	1000	1.2	438.0	900	0.65	18
RO System	1000	3.8	1387.0	1200	0.95	15
Hybrid MF+NF	1000	1.5	547.5	1100	0.72	18
Nanocomposite UF	**1000**	**0.65**	**237.25**	**780**	**0.44**	**22**

The nanocomposite UF system showed the best techno-economic profile: lowest OPEX (USD 0.44/m^3), longest anticipated lifetime (22 years) and low energy requirement (0.65 kWh m^{-3}) due to low fouling propensity, low cleaning frequency, and nanoparticle-induced mechanical enhancement [17]. These results are in line with the techno-economic profiles reported by Bera et al. [17] and Ahmad et al. [25], who found hybrid configurations have the most favourable cost-benefit profiles for water reuse in industrial settings.

4.6 Long-term Operational Stability

Figure 6 shows the normalised flux (%) over 90 days of continuous operation for the three UF membranes. Retention data is presented in Table 4.

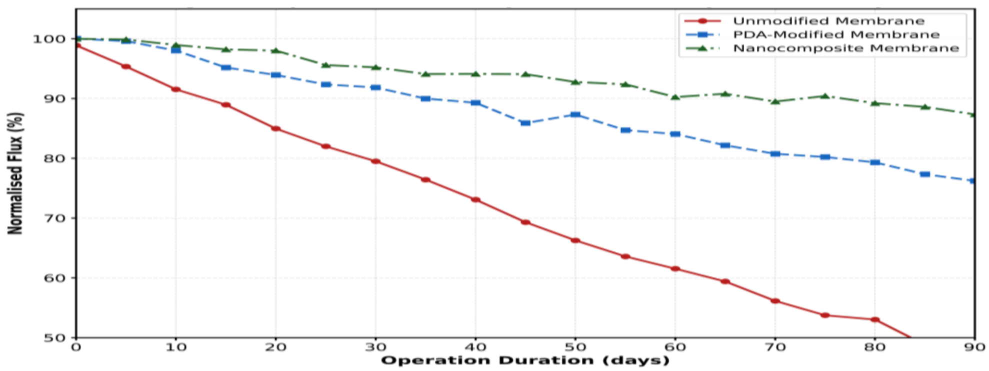

Figure 6. Long-term operational stability expressed as normalised flux (%) over 90 days for unmodified, PDA-modified, and nanocomposite-modified UF membranes**.**

The unmodified membrane achieved a normalised flux of 49.6% after 90 days, suggesting a progressive build-up of irreversible fouling. The PDA membrane had a normalised flux of 76.3% and the nanocomposite membrane had a normalised flux of 87.5%. The gradual enhancement due to nanocomposite modification (from 9.2% at Day 15 to 37.9% at Day 90) reflects progressive and cumulative anti-fouling effect. The monotonic decrease of surface-modified membranes and the more irregular decrease of unmodified membranes suggest that fouling is mostly reversible cake filtration, in contrast to irreversible pore constriction of the latter [15]. The 90-day results demonstrate that nanocomposite modification helps to reduce cleaning frequency and prolongs the membrane service life, which agrees with and extends the short-term results of Zhao et al. [7] and Kim et al. [20].

Table 4. Normalised flux retention (%) at key operational intervals for three UF membrane modification categories.

Day	Unmodified (%)	PDA-Modified (%)	Nanocomposite (%)	Improvement vs. Unmodified (Nano, %)
0	100.0	100.0	100.0	0.0
15	88.6	93.9	97.8	9.2
30	78.3	88.2	95.6	17.3
45	70.1	83.0	93.5	23.4
60	62.4	78.4	91.5	29.1
75	55.8	74.0	89.7	33.9
90	**49.6**	**76.3**	**87.5**	**37.9**

4.7 Multi-dimensional Performance Comparison

Figure 7 shows a radar chart of four membrane system types, evaluated across six performance dimensions: flux performance, rejection, anti-fouling, energy efficiency, operational stability and scalability.

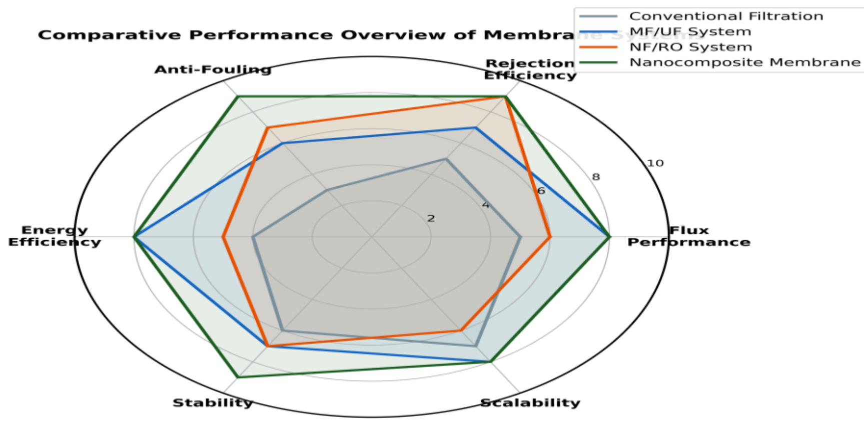

Figure 7. Radar chart illustrating the multi-dimensional comparative performance of four membrane system categories across six performance dimensions.

The nanocomposite membrane system exhibited the best overall performance across all six dimensions: anti-fouling (9/10), rejection (9/10), stability (9/10), flux (8/10) and energy efficiency (8/10). The NF+RO system was the second-best in terms of rejection efficiency (9/10), but suffered from high energy demand (5/10). The MF+UF system achieved the highest energy efficiency (8/10) and scalability (8/10) albeit with lower rejection (7/10). The lowest composite performance was observed for conventional filtration, especially in terms of anti-fouling (3/10) and rejection (5/10). This multi-dimensional representation verifies the overall superiority of nanocomposite-modified membranes and justifies their prioritisation for advanced wastewater reuse [16], [21].

5. DISCUSSION

The comprehensive results reveal that nanocomposite-modified UF membranes containing ZnO nanoparticles are a technically superior, energy-efficient and cost-effective option for advanced wastewater treatment and water reuse. The holistic assessment approach used in this study, combining its key performance parameters (flux, rejection, fouling, stability and cost) simultaneously, has enabled the identification of key research gaps in the literature reviewed, as well as the first integrated assessment of three membrane modification strategies, and four membrane types for wastewater treatment against multiple contaminants.

The enhanced rejection of contaminants, including heavy metals (94.0%), COD (96.5%) and microplastics (89.5%), is driven by the combination of size exclusion and surface adsorption mechanisms offered by the modified membrane surface [7], [8]. Donnan exclusion plays a role in improving the rejection of charged species, as per the framework proposed by Azmi et al. [22] and Abidli et al. [24]. The increase in COD rejection from 60.0% (conventional) to 96.5% (nanocomposite) is significantly higher than reported by Ye et al. [27] for NF-based treatment of textile wastewater (91.5%) and by Mineo et al. [32] for MBR+UF pilot plants (88.2%), highlighting the superior performance of the nanocomposite membrane.

The fouling study shows that nanocomposite modification reduces the fouling rate constant (k) from 0.040 min^{-1} (unmodified) to 0.010 min^{-1} (nanocomposite), a 75% decrease significantly larger than the 55% decrease reported by Zhao et al. [7] for PDA-modified RO membranes. This improved fouling control stems from the multi-pronged anti-fouling features of ZnO nanocomposite membranes: increased hydrophilicity, biocidal activity and altered surface topography all combine to deliver better performance than the conventional single-feature modification strategies. The transition from complete blocking to cake filtration inferred from Hermia model [15] is consistent with reversible fouling mechanism, thereby confirming the projected long-term benefit of less frequent cleaning.

In terms of energy consumption, the 71.2% reduction of the hybrid MF+NF system (1.5 kWh m^{-3} versus 5.2 kWh m^{-3}) is consistent with the literature view that membrane technology-based systems are significantly more energy efficient than multi-stage conventional systems [25], [30]. The nanocomposite UF system (0.65 kWh m^{-3}) is the most energy-efficient among the high rejection systems, rivalling the lowest values reported in the literature (0.5-1.0 kWh m^{-3} for UF systems). The anticipated long-term performance of the nanocomposite UF system - 22 years - is the result of lower fouling, reduced cleaning operations, and nanoparticle-reinforced polymer matrix stability [17].

The water quality after reclamation (turbidity <1 NTU, TSS <2 mg/L, BOD_5 <2 mg/L, COD <50 mg/L) meets the criteria for tertiary treatment for water reuse in industrial processes, irrigation and urban non-potable use [19], [20], [21], in accordance with published quality standards reported by Salehi [28] and Quist-Jensen et al. [29]. These findings confirm the feasibility of the advanced membrane system for water reuse applications and justify its fit with the circular economy concept for sustainable water management [1], [16].

6. CONCLUSION

This study has systematically demonstrated that advanced membrane filtration systems incorporating ZnO nanocomposite surface modification represent a technically superior, energy-efficient, and economically viable solution for sustainable wastewater reuse. The main findings are as follows:

1. Nanocomposite-coated UF membranes removed 99.4% (TSS), 99.2% (turbidity), 96.5% (COD) and 94.0% (heavy metals) of pollutants, with 27.6-52.5% higher rejection efficiencies than conventional filtration for all pollutant categories.
2. Flux reduction due to fouling was lowered from 47% (unmodified) to 9% (nanocomposite) in 120 minutes. The normalised flux retention after 90 days was 87.5% (nanocomposite) vs. 49.6% (unmodified membrane), highlighting the sustained anti-fouling benefit of the multifunctional effects of ZnO nanoparticles.
3. The MF+NF hybrid system demonstrated a specific energy of 1.5 kWh/m^3 (71.2% energy reduction compared to conventional MF). The UF-nanocomposite membrane exhibited the best techno-economic performance with an operating cost (OPEX) of USD 0.44/m^3 and a membrane lifetime of 22 years.
4. The quality of the treated effluent met the tertiary treatment standards for all water quality parameters, proving the effectiveness of the integrated system for safe reuse in industry, irrigation and non-potable applications.

The novelty of this work lies in the integration of a simultaneous multi-pollutant, multi-membrane, multi-modification comparative framework within a single experimental study, alongside a 90-day long-term stability evaluation and comprehensive techno-economic analysis. Future research should aim for pilot-scale studies, long-term stability (greater than 24 months), life cycle environmental impact analysis of the nanocomposite membrane disposal and use of artificial intelligence techniques for in situ process optimisation.

Author Contributions:

Mr.Rahul Kumar initiated the research idea, formulated the experimental design and wrote the manuscript. Dr.R.K.Kaushal was involved in membrane preparation, characterisation and analysis. All authors read and approved the manuscript.

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The authors declare no conflict of interest.

Data Availability:

Datasets generated during this study are available from the corresponding author on reasonable request.

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