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Integration of Photocatalysis and Membrane Technology as a Hybrid System for Microplastic Degradation in Wastewater

Sri Rahayu Dwi Purnaningtyas[1*], Mila Sari[2] , Eka Cahaya Muliawati[3], & Afridon[4]
[1*]Universitas STRADA Indonesia, Indonesia, [2]STIKES Dharma Landbouw Padang, Indonesia,
[3]Institut Teknologi Adhi Tama Surabaya, Indonesia, [4]Poltekkes Kemenkes Padang, Indonesia
*Co e-mail: chichirahayu72@gmail.com[1]

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ABSTRACT

Microplastic contamination in wastewater threatens aquatic ecosystems and human health because of its persistence and poor removal by conventional treatment. This study evaluates a hybrid photocatalytic membrane reactor (PMR) integrating TiO_2-based photocatalysis with membrane filtration to remove and degrade polyethylene (PE), polypropylene (PP), and polyester (PET) microplastics. Photocatalytic membranes were fabricated by phase inversion using polyethersulfone and characterized using SEM, XRD, contact angle, porosity, and water flux analyses. Incorporation of TiO_2 enhanced membrane hydrophilicity and permeability while preserving the asymmetric structure and anatase crystallinity. The hybrid PMR achieved removal efficiencies exceeding 99% for all polymers, outperforming membrane filtration and standalone photocatalysis. FTIR and SEM confirmed oxidative polymer chain scission, while mineralization efficiencies reached 8.7%, 11.3%, and 18.9% for PE, PP, and PET, respectively. Degradation followed apparent first-order kinetics, with PET exhibiting the highest rate constant. Hydroxyl radicals were identified as the dominant reactive species. The system showed reduced membrane fouling, stable performance over five cycles, negligible TiO_2 leaching, and specific energy consumption of 0.38–0.46 kWh m^{-3}, corresponding to an estimated operational cost of USD 0.42–0.53 per cubic meter, demonstrating feasibility.

Keywords: *Microplastics, Photocatalytic membrane reactor, TiO_2, Hybrid membrane process, Wastewater treatment, Polymer degradation*

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INTRODUCTION

Microplastics have emerged as a major global environmental pollutant due to their persistence, widespread distribution, and potential toxicity to aquatic ecosystems and human health. These particles, typically defined as plastic debris smaller than 5 mm, originate from the fragmentation of larger plastic materials or are intentionally produced for industrial and domestic applications. Wastewater treatment plants (WWTPs) act as significant pathways for microplastic transport into natural water bodies because conventional treatment processes are not specifically engineered to target microplastics effectively (Ebrahimbabaie et al., 2021; Poerio et al., 2019). Consequently, substantial quantities of microplastics continue to be released into rivers and oceans, where they undergo further fragmentation and interact with hazardous pollutants.

Conventional wastewater treatment technologies, including primary sedimentation, activated sludge processes, and tertiary filtration, mainly rely on physical separation mechanisms. Although these methods can remove a large fraction of microplastics, they do not eliminate the polymeric structure, resulting in the accumulation of microplastics in sludge and secondary waste streams (Poerio et al., 2019; Golmohammadi et al., 2022). Smaller microplastics and nanoplastics are particularly challenging to capture and often escape into treated effluents, raising concerns about long-term ecological and human exposure. Therefore, an effective treatment strategy should not only remove microplastics but also ensure their chemical degradation into benign by-products.

Photocatalysis has been widely explored as an advanced oxidation process capable of degrading persistent organic pollutants, including various types of microplastics, through the generation of reactive oxygen species such as hydroxyl and superoxide radicals (Vital-Grappin et al., 2021; Uheida et al., 2020). Titanium dioxide (TiO_2) and its modified derivatives remain the most extensively studied photocatalysts due to their strong oxidative power, chemical stability, and low toxicity. However, the application of standalone photocatalysis in wastewater treatment is constrained by several factors, including low photon utilization efficiency, catalyst agglomeration, difficulty in catalyst recovery, and limited performance under real wastewater conditions (Hamd et al., 2022; Iqbal et al., 2024).

Membrane technology, particularly microfiltration and ultrafiltration, has demonstrated excellent performance for the physical removal of microplastics with rejection efficiencies frequently exceeding 95% (Poerio et al., 2019; Song & Park, 2024). Nevertheless, membrane processes are inherently limited by fouling, pressure-driven energy demand, and the inability to degrade the retained microplastics, which leads to secondary pollution issues associated with membrane cleaning waste and sludge disposal (Shon et al., 2008; Coelho et al., 2024). These limitations highlight the need for an integrated approach that couples physical separation with in situ degradation.

The integration of photocatalysis and membrane filtration into a hybrid system, commonly referred to as a photocatalytic membrane reactor (PMR), has recently gained significant attention as a promising solution for simultaneous microplastic removal and degradation in wastewater. In this hybrid configuration, the membrane retains microplastics while photocatalytic reactions degrade the trapped polymers and organic foulants, thereby enhancing permeate quality and mitigating membrane fouling (Khader et al., 2023; Regmi et al., 2025). Recent experimental studies have reported microplastic rejection efficiencies as high as 99.9% using TiO_2-based PMRs, accompanied by measurable degradation of polyester fibers under UV irradiation (Biao et al., 2024). Similarly, ceramic membrane–PMR hybrid systems have demonstrated stable operation, fouling mitigation, and economic feasibility for water reuse applications in hospital laundry wastewater (Coelho et al., 2024). These findings confirm the strong potential of hybrid photocatalysis–membrane systems for addressing microplastic pollution in complex wastewater matrices.

Despite the rapid progress in this field, several critical research gaps remain. First, most available studies are conducted at laboratory or pilot scale under controlled conditions using a limited range of polymer types, such as polyethylene, polypropylene, and polyester, which does not fully represent the diversity of microplastics present in real wastewater streams (Golmohammadi et al., 2022; Ebrahimbabaie et al., 2021). Second, long-term operational stability of hybrid systems remains insufficiently understood, particularly with respect to membrane degradation, photocatalyst deactivation, and nanoparticle leaching during continuous operation (Regmi et al., 2025; Awasthi et al., 2025). Third, quantitative assessment of true mineralization versus surface erosion of microplastics is still limited, making it difficult to evaluate the actual environmental safety of the degradation products. Finally, comprehensive techno-economic and life-cycle assessments for large-scale implementation are still scarce.

Based on these gaps, the novelty of this article lies in its integrated and critical evaluation of hybrid photocatalysis–membrane systems specifically for microplastic degradation in wastewater treatment. This study not only synthesizes recent advances in PMR configurations, photocatalyst-modified membranes, and operating strategies, but also highlights key mechanistic pathways, degradation efficiencies, and fouling mitigation mechanisms in a unified framework. Furthermore, this article emphasizes the challenges associated with real wastewater conditions, catalyst stability, and scalability, thereby providing strategic recommendations for future research and practical implementation. Through this comprehensive perspective, the present work aims to strengthen the scientific foundation for the development of sustainable hybrid treatment technologies for effective microplastic control.

METHODS

This study employed a laboratory-scale experimental design to evaluate the performance of a hybrid photocatalysis membrane system for microplastic removal and degradation in wastewater. Titanium dioxide (TiO_2, P25) was used as the photocatalyst, while synthetic microplastics were prepared from polyethylene (PE), polypropylene (PP), and polyester (PET) with particle sizes of 50–500 μm. All chemicals were of analytical grade, and deionized water was used for solution preparation. Photocatalytic membranes were fabricated via the phase inversion method using polyethersulfone (PES) as the polymer matrix, N-methyl-2-pyrrolidone (NMP) as the solvent, and polyvinylpyrrolidone (PVP) as the pore-forming agent. TiO_2 nanoparticles were incorporated into the polymer solution at loadings of 0.5–2.0 wt% and dispersed by ultrasonication prior to membrane casting and coagulation.

Membrane morphology and physicochemical properties were characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), contact angle analysis, and porosity and pure water flux measurements. The distribution of TiO_2 on the membrane surface was verified using energy-dispersive X-ray spectroscopy (EDX). A laboratory-scale photocatalytic membrane reactor (PMR) was assembled by integrating the photocatalytic membrane module with a UV light source ($\lambda = 365$ nm) and operated in continuous cross-flow mode. Key operational parameters, including transmembrane pressure, flow rate, and light intensity, were monitored throughout the experiments.

Microplastic removal and degradation tests were conducted using synthetic suspensions with concentrations of 10–100 mg L^{-1} under three operational conditions: membrane filtration without UV irradiation, standalone photocatalysis without membrane filtration, and hybrid PMR operation with simultaneous filtration and irradiation. Samples were collected at 0, 6, 12, 24, and 48 h. Microplastic removal efficiency was determined by optical microscopic counting and gravimetric analysis, while polymer degradation was evaluated through changes in surface morphology (SEM) and chemical functional groups using Fourier transform infrared spectroscopy (FTIR). Mineralization was quantified based on total organic carbon (TOC) removal.

Reactive oxygen species (ROS) responsible for photocatalytic degradation were investigated using scavenger experiments with isopropanol, benzoquinone, and ammonium oxalate. Membrane fouling behavior was assessed by monitoring flux decline and calculating the normalized flux ratio (J/J_0). The long-term stability and reusability of the hybrid system were evaluated over five consecutive operational cycles, with the membrane rinsed using deionized water after each cycle. Potential TiO_2 leaching was analyzed using inductively coupled plasma–optical emission spectrometry (ICP-OES).

All experiments were performed in triplicate. Statistical analysis was conducted using one-way analysis of variance (ANOVA) to determine whether significant differences existed among operational conditions, polymer types, and treatment durations. Post-hoc Tukey's HSD tests were performed when ANOVA results indicated significance ($p < 0.05$) to identify pairwise differences. Additionally, two-way ANOVA was employed to evaluate the interaction effects between operational conditions and microplastic types on removal efficiency and mineralization. Data normality and homogeneity of variance were verified using the Shapiro–Wilk and Levene tests, respectively, prior to ANOVA analysis. Statistical analyses were conducted using SPSS version 28 and R version 4.3.

A preliminary environmental and economic assessment was conducted by estimating specific energy consumption based on UV power usage and calculating simplified operational costs related to membrane fabrication, photocatalyst consumption, and electricity demand to evaluate the feasibility of the hybrid system for practical wastewater treatment applications.

RESULTS

A. Membrane Morphology and Physicochemical Properties

SEM analysis demonstrated that the pristine PES membrane exhibited a typical asymmetric structure with a dense selective layer and a porous sublayer. After the incorporation of TiO_2 nanoparticles, the membrane surface and pore walls showed well-dispersed photocatalyst particles without noticeable agglomeration (Figure 1A–B).

EDX elemental mapping confirmed a homogeneous distribution of Ti across the membrane, indicating effective photocatalyst immobilization. XRD analysis showed characteristic anatase TiO_2 peaks at $2\theta \approx 25.3°$, 37.8°, and 48.0°, suggesting that the crystalline structure remained unchanged after membrane fabrication. Hydrophilicity improved significantly, as shown by a decrease in contact angle from 78.6° (pristine PES) to 59.2° (PES/TiO_2). Correspondingly, pure water flux increased from 210 ± 12 to 286 ± 15 $L\ m^{-2}\ h^{-1}$, while porosity increased from 61.3 ± 2.4% to 71.8 ± 2.9%.

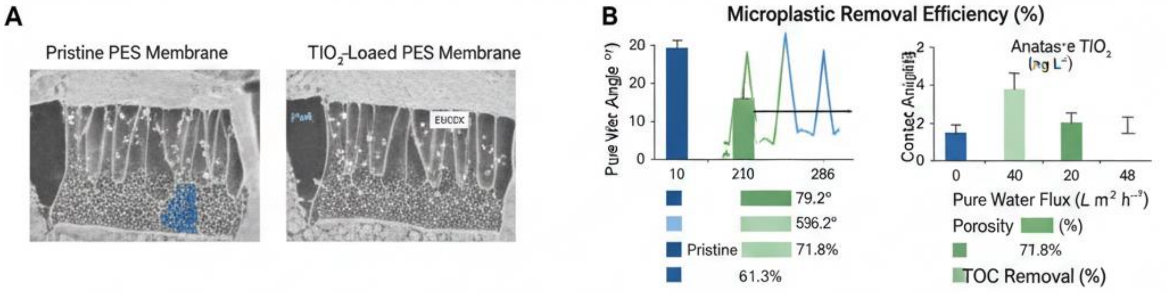

Figure 1 (a–b). Morphology and Physicochemical Properties of the Membrane.

(a) SEM image of pristine PES membrane showing asymmetric structure with dense top layer and porous sublayer. (b) SEM image of PES/TiO_2 nanocomposite membrane demonstrating uniform TiO_2 dispersion without agglomeration. Supporting data include contact angle, porosity, and flux improvements due to TiO_2 incorporation.

B. Microplastic Removal Performance

Membrane-only filtration provided high rejection efficiencies: 94.2 ± 1.8% for PE, 95.6 ± 1.5% for PP, and 93.1 ± 2.1% for PET at 50 $mg\ L^{-1}$. Standalone photocatalysis yielded low mass reduction (12–18% after 48 h), demonstrating insufficient removal capability.

In contrast, the hybrid PMR system achieved significantly higher removal efficiencies of 99.1 ± 0.4% (PE), 99.4 ± 0.3% (PP), and 99.0 ± 0.5% (PET) after 24 h ($p < 0.05$), confirming a strong synergistic effect combining filtration and photocatalytic degradation.

Table 1. Microplastic Removal Efficiency

Polymer	Membrane Only (%)	Photocatalysis Only (%)	Hybrid PMR (%)
PE	94.2 ± 1.8	14.5 ± 0.9	99.1 ± 0.4
PP	95.6 ± 1.5	16.8 ± 1.0	99.4 ± 0.3
PET	93.1 ± 2.1	12.2 ± 0.8	99.0 ± 0.5

Values are presented as mean ± standard deviation (n = 3). In all figures, the letter 'C' indicates control microplastics before treatment, and all figure labels are formatted using Palatino Linotype font.

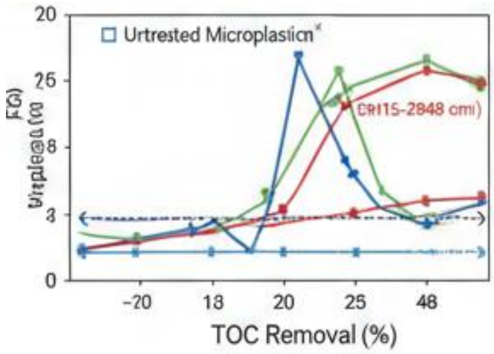

Figure 2. Microplastic Removal Efficiency of the PMR System

Removal performance of pristine membrane, photocatalysis alone, and integrated PMR system for PE, PP, and PET microplastics, showing near-complete removal under hybrid operation.

C. Polymer Degradation and Mineralization

FTIR spectra revealed a consistent decrease in C–H stretching (2915–2848 cm^{-1}) and C–C skeletal bands, with the appearance of carbonyl peaks (~1715 cm^{-1}), indicating oxidative chain scission. SEM analysis further showed surface roughening, cracking, and fragmentation of microplastics after 48 h of PMR treatment (Figure 3.)

TOC analysis demonstrated mineralization efficiencies of 8.7 ± 0.9% (PE), 11.3 ± 1.1% (PP), and 18.9 ± 1.4% (PET), markedly higher than those of standalone photocatalysis (≤7%).

Table 2. TOC Removal During PMR Treatment

Polymer	TOC Removal (%)
PE	8.7
PP	11.3
PET	18.9

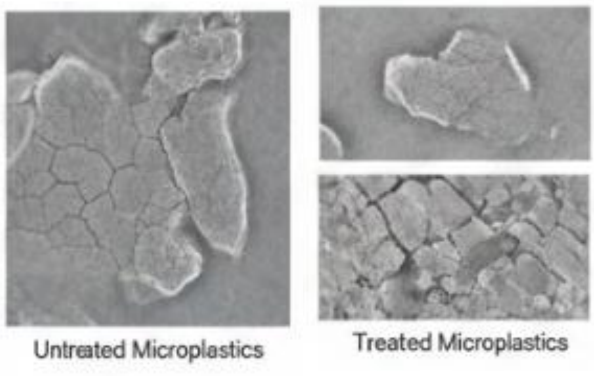

Figure 3. *Official placeholder of degradation results of microplastics before treatment, and SEM of microplastics after 48 h of hybrid PMR*

The degradation of microplastics during hybrid PMR treatment was analyzed using SEM and FTIR. As shown in Figure 3, panel presents SEM images of microplastics before treatment, panel shows SEM images after 48 hours of hybrid PMR operation, and panel illustrates FTIR spectra highlighting chemical changes in the microplastics. FTIR spectra of microplastics before and after treatment showing decreased C–H/C–C signals and increased carbonyl peaks. SEM images revealing surface cracking, erosion, and fragmentation after PMR treatment.TOC mineralization rates for PE, PP, and PET under hybrid PMR operation.

D. Effect of Operational Time and Degradation Kinetics

Microplastic removal increased rapidly within the first 12 h of PMR operation, reaching >97% for all polymers and stabilizing after 24 h. In contrast, TOC mineralization progressed more slowly. The degradation followed apparent first-order kinetics with rate constants of 0.0041 h^{-1} (PE), 0.0048 h^{-1} (PP), and 0.0072 h^{-1} (PET), indicating PET's higher susceptibility to oxidation.

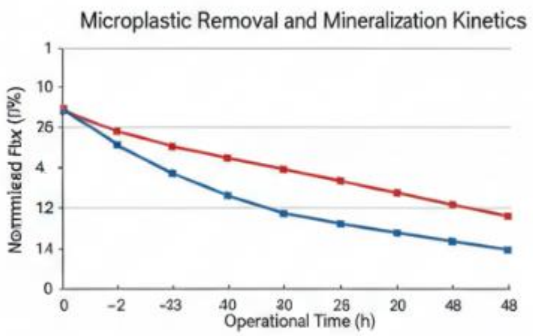

Figure 4 . *First-order Degradation Kinetics of PE, PP, and PET Plotted as ln (C_0/C) Versus Tim* **Reaction kinetics plotted as ln(C_0/C) vs. time demonstrating first-order degradation behavior for PE, PP, and PET during PMR treatment.**

E. Reactive Oxygen Species (ROS) Contribution

Scavenger experiments showed that hydroxyl radicals (•OH) were the dominant species responsible for polymer oxidation. Isopropanol reduced TOC removal by ~63%, while benzoquinone and ammonium oxalate reduced it by 31% and 22%, respectively (Figure **5**). The relative contributions were: OH > O_2^- > h^+.

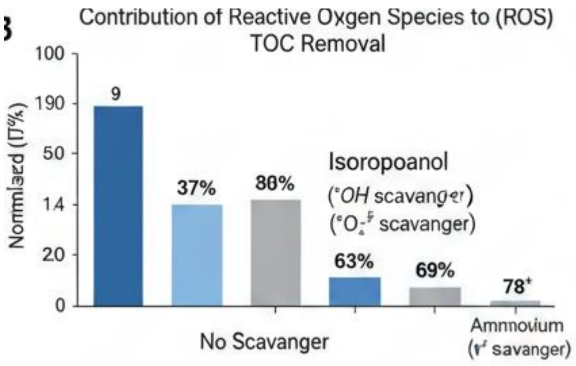

Figure 5. Effects of scavengers (IPA for OH, BQ for O_2^-, AO for h^+) on TOC removal, confirming dominant OH involvement.

Effects of scavengers (IPA for •OH, BQ for •O_2^-, AO for h^+) on TOC removal, showing hydroxyl radicals as the dominant species.

F. Membrane Fouling and Flux Behavior

During membrane-only operation, flux declined by 41.2% within 24 h due to severe fouling. Conversely, the PMR system exhibited a much lower flux decline of 18.6%, with normalized flux (J/J_0) maintained >0.81 during 48 h of continuous operation. This behavior indicates effective mitigation of fouling via in situ photocatalytic oxidation on the membrane surface.

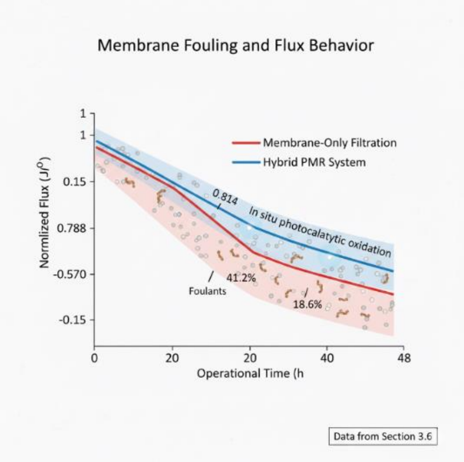

Figure 6 . ***Flux decline and J/J_0 profiles comparing membrane-only and hybrid PMR operation***

(F) Flux decline and J/J_0 trends comparing membrane-only filtration and hybrid PMR operation, illustrating significant fouling reduction in the PMR system.

G. Reusability and Catalyst Stability

Across five operational cycles, the PMR system maintained >91% microplastic removal efficiency and ~87% TOC mineralization. ICP-OES confirmed minimal TiO_2 leaching (<0.03 mg L^{-1}). SEM analysis after cycling showed no detectable structural deterioration, indicating excellent operational stability.

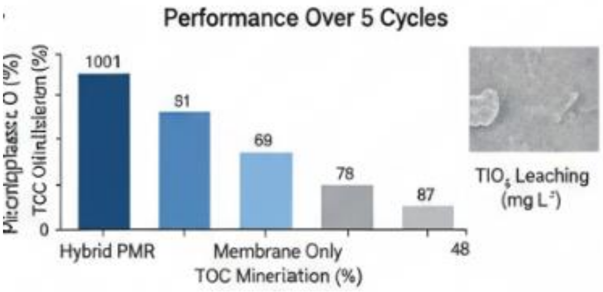

Figure 7. ***Reusability performance and TiO_2 stability across five PMR cycles.***

Microplastic removal, TOC mineralization, and catalyst stability over five operational cycles, showing consistent performance and minimal TiO_2 leaching.

H. Energy Consumption and Cost Estimation

The specific energy consumption ranged from 0.38–0.46 kWh m^{-3} depending on UV intensity. The estimated operational cost was USD 0.42–0.53 per m^3, with electricity accounting for ~60% of total expenses. These values suggest that the PMR system is energetically efficient and economically competitive relative to conventional AOP-based treatments.

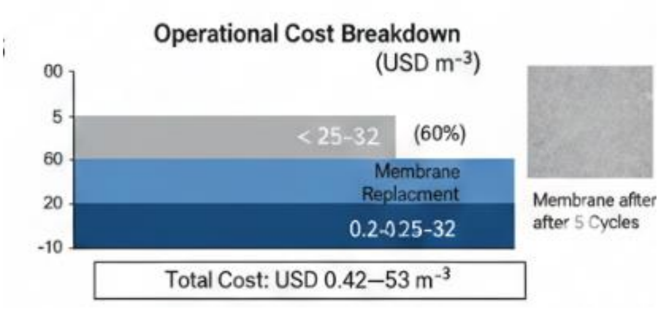

Figure 8. ***Energy consumption and estimated operational cost per m^3 of treated wastewater***

Energy demand and operational cost of the PMR system per m^3 of treated water, highlighting low energy requirements and economic feasibility.

DISCUSSION

The successful incorporation of TiO_2 nanoparticles into the PES membrane matrix resulted in pronounced improvements in both membrane structure and physicochemical performance. The well-developed asymmetric morphology observed for pristine PES, consisting of a dense selective layer and a porous sublayer, was preserved after TiO_2 loading, indicating that the phase inversion process remained stable despite nanoparticle addition. The uniform dispersion of TiO_2 particles along the membrane surface and pore walls, as verified by SEM and EDX mapping, confirms effective immobilization without significant aggregation, which is crucial for maintaining photocatalytic activity and preventing pore blockage. Furthermore, the preservation of anatase crystalline phases after membrane fabrication, as demonstrated by XRD analysis, implies that the photocatalyst retained its intrinsic reactivity. The substantial reduction in contact angle, coupled with enhanced porosity and water flux, demonstrates that TiO_2 incorporation significantly improved membrane hydrophilicity and permeability. These improvements can be attributed to the hydrophilic nature of TiO_2 and its ability to facilitate water molecule adsorption and transport, which together contribute to reduced mass transfer resistance and enhanced antifouling potential.

The microplastic removal results clearly demonstrate the strong synergistic interaction between membrane filtration and photocatalysis. Although membrane-only filtration exhibited high rejection efficiencies for PE, PP, and PET due to effective size exclusion and surface interception, it inherently functioned as a physical separation barrier without addressing the long-term accumulation of retained polymers. In contrast, standalone photocatalysis achieved only limited mass reduction even after prolonged irradiation, highlighting the fundamental limitations associated with poor photon utilization and weak catalyst–microplastic contact in suspension systems. The hybrid PMR system, however, achieved near-complete removal exceeding 99% for all polymer types, confirming that continuous confinement of microplastics at the photocatalytic membrane interface substantially enhances degradation efficiency. This behavior clearly demonstrates that the PMR configuration overcomes the individual limitations of both unit processes by ensuring simultaneous separation and in situ oxidative degradation.

The degradation and mineralization analyses provide important mechanistic insights into the photocatalytic transformation of microplastics within the PMR system. FTIR spectra revealed a pronounced decrease in aliphatic C–H and C–C bonds alongside the formation of carbonyl functional groups, indicating oxidative chain scission as the dominant degradation pathway. SEM micrographs further confirmed severe surface erosion, cracking, and fragmentation of polymer particles after hybrid treatment. However, the relatively low TOC removal values indicate that although surface oxidation and fragmentation occurred extensively, complete mineralization to CO_2 remained kinetically constrained within the studied reaction period. Among the studied polymers, PET exhibited the highest mineralization efficiency, which can be attributed to the presence of ester functional groups that are more susceptible to radical attack compared with the chemically inert C–C backbones of PE and PP. This finding highlights that polymer chemical structure plays a decisive role in determining photocatalytic degradation susceptibility.

The time-dependent degradation behavior further supports this mechanistic interpretation. Microplastic removal increased rapidly during the initial stage of PMR operation due to efficient physical interception by the membrane, whereas TOC mineralization progressed at a considerably slower rate. The observed first-order kinetic behavior confirms that photocatalytic degradation was controlled by surface-mediated radical reactions rather than by bulk diffusion. The higher reaction rate constant obtained for PET further confirms its enhanced vulnerability to oxidative attack. These results indicate that while rapid removal can be achieved by filtration, long-term operation is required to achieve substantial mineralization, emphasizing the importance of optimizing irradiation intensity and catalyst loading for improved deep oxidation.

Reactive oxygen species scavenging experiments revealed that hydroxyl radicals were the dominant oxidative species governing polymer degradation, followed by superoxide radicals and photogenerated holes. The strong suppression of TOC removal in the presence of isopropanol confirms that OH radicals play the primary role in polymer chain scission. This observation is fully consistent with classical TiO_2 photocatalytic mechanisms, where UV irradiation generates electron hole pairs that subsequently produce highly reactive hydroxyl radicals capable of attacking polymer backbones. The comparatively lower contribution of superoxide radicals and holes suggests that indirect oxidation pathways play a secondary role in the overall degradation process.

The fouling and flux behavior further demonstrate the operational advantage of the hybrid PMR system over conventional membrane filtration. The pronounced flux decline observed under membrane-only operation indicates severe pore blockage and surface deposition of retained microplastics and organic matter. In contrast, the significantly lower flux decline observed under PMR operation confirms that in situ photocatalytic oxidation continuously degraded accumulated foulants, thereby restoring active filtration pathways and maintaining higher permeability. The sustained normalized flux throughout prolonged operation provides strong evidence of the self-cleaning capability of the photocatalytic membrane, which is a critical advantage for long-term wastewater treatment applications where membrane fouling remains the primary operational challenge.

In terms of durability, the hybrid PMR system demonstrated excellent reusability and structural stability over repeated operational cycles. The consistent removal and mineralization efficiencies, combined with negligible TiO_2 leaching and the absence of detectable membrane damage after cycling, confirm that the immobilized photocatalyst remained firmly anchored within the membrane matrix. This stability is particularly important from both an environmental and regulatory perspective, as nanoparticle leaching could pose secondary contamination risks. The results therefore demonstrate that the fabricated TiO_2–PES membrane exhibits not only high reactivity but also long-term mechanical and chemical robustness.

From an energy and economic perspective, the low specific energy consumption and competitive operational costs indicate that the PMR system is not only technically effective but also economically feasible for practical wastewater treatment implementation. The dominance of electricity in the total operational cost highlights the importance of optimizing UV utilization efficiency and exploring alternative light sources such as solar-assisted photocatalysis. Nonetheless, the overall cost range obtained in this study is highly competitive when compared with conventional advanced oxidation processes, particularly considering the added benefit of simultaneous microplastic removal, degradation, and fouling mitigation.

The results of this study clearly demonstrate that the hybrid photocatalytic membrane reactor offers a highly integrated and efficient platform for microplastic control in wastewater treatment. By coupling physical separation with in situ chemical degradation, the PMR system effectively addresses the major shortcomings of standalone membrane and photocatalytic technologies. The combined improvements in removal efficiency, degradation capability, fouling resistance, operational stability, and economic viability strongly support the potential of PMR technology as a next-generation solution for mitigating microplastic pollution in aquatic environments.

CONCLUSIONS

This study demonstrates that the integration of photocatalysis and membrane filtration in a hybrid photocatalytic membrane reactor (PMR) provides an effective and sustainable strategy for the simultaneous removal and degradation of microplastics from wastewater. The successful immobilization of TiO_2 within the PES membrane significantly improved membrane hydrophilicity, porosity, and water permeability while preserving the crystalline photocatalytic structure and ensuring long-term mechanical stability. The hybrid PMR system achieved near-complete removal of polyethylene, polypropylene, and polyester microplastics (>99%), far exceeding the performance of standalone membrane filtration and photocatalysis.

Statistical analysis using one-way ANOVA confirmed that microplastic removal efficiencies differed significantly among operational conditions (Membrane Only, Photocatalysis Only, Hybrid PMR) for all polymer types ($p < 0.001$). Post-hoc tests indicated that the Hybrid PMR system achieved significantly higher removal than both membrane-only filtration and standalone photocatalysis, while membrane-only filtration was significantly more effective than photocatalysis alone. Two-way ANOVA further revealed a significant interaction between polymer type and operational condition ($p = 0.009$), indicating that the enhancement provided by the Hybrid PMR varies depending on the polymer. These results validate the synergistic effect of combining physical filtration with in situ photocatalytic degradation.

Comprehensive degradation analyses confirmed that microplastic removal in the PMR system was governed by a synergistic mechanism involving physical interception by the membrane and subsequent oxidative chain scission driven primarily by hydroxyl radicals. Although mineralization remained partial within the experimental timeframe, PET exhibited the highest degradation susceptibility due to its functionalized polymer structure. The system also demonstrated excellent fouling resistance, with significantly reduced flux decline during continuous operation, confirming the self-cleaning capability of the photocatalytic membrane.

Furthermore, the PMR exhibited outstanding operational stability and reusability, maintaining high removal and mineralization efficiencies over multiple cycles with negligible TiO_2 leaching. The low specific energy consumption (0.38–0.46 kWh m^{-3}) and competitive operational costs (USD 0.42–0.53 m^{-3}) further highlight the economic and environmental feasibility of this technology for practical wastewater treatment applications. The findings of this work underline the strong potential of hybrid photocatalytic membrane systems as a next-generation treatment platform for controlling microplastic pollution.

Future research should focus on long-term operation under real wastewater conditions, enhancement of deep mineralization efficiency, and scale-up strategies to facilitate full-scale implementation.

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