



Research Article

An MXene–Titania Nanofiltration Membrane with Thermocatalytic Activity for Water Pollution Removal

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Abstract: Herein, we designed a multifunctional thermocatalytic nanofiltration membrane, which consists of a MXene–TiO₂ nanocomposite incorporated within a humic acid-like crosslinked graphene oxide (GO–HAL) matrix on the surface of polyethersulfone support. The membrane combined molecular separation, dark thermocatalytic degradation, and fouling mitigation without external irradiation and added oxidants. Model feeds were Bisphenol A (BPA) and effluent from a municipal wastewater-treatment-plant. The MTG-98.6 composition accomplished nearly 52% BPA removal in 120 min at 50 °C, and an apparent pseudo-first-order rate constant of $(6.2 \pm 0.3) \times 10^{-3} \text{ min}^{-1}$ on a mass basis was higher than that of the unsupported MXene–TiO₂. It yielded a membrane with a water permeance of $1.3 \text{ L m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$. Feed BPA after 18 h of crossflow filtration decreased from $10.19 \pm 0.03 \text{ mg L}^{-1}$ to 4.1 mg L^{-1} , whereas the permeate BPA concentration remained stable ($0.33 \pm 0.09 \text{ mg L}^{-1}$) and rejection decreased only from approximately 97% to 94%. The permeate TOC from wastewater tests was also lower than for the GO–HAL reference. XPS confirmed retention of the catalytic phase after filtration, demonstrating chemical stability under the applied conditions and operational repeatability. Acute ecotoxicity tests indicated low toxicity to *Aliivibrio fischeri* and *Raphidocelis subcapitata*, whereas *Daphnia magna* survival depended on nanocomposite concentration and temperature. These results support MXene–TiO₂/GO–HAL membranes for simultaneous nanofiltration and thermocatalytic removal of emerging organic contaminants using low-grade heat.

Keywords: Antifouling; Bisphenol a removal; MXene–TiO₂ nanocomposite; Nanofiltration; Self-cleaning membrane

1. Introduction

Contaminants of emerging concern (CECs) are a growing concern in recent years due to their ubiquitous presence in both natural and engineered aquatic systems (Mahmood et al., 2022; Patel et al., 2019; Tang et al., 2020). CECs comprise a wide variety of anthropogenic compounds that are continuously released into the environment from domestic, industrial, agricultural, and pharmaceutical activities. Many of these persistent micropollutants are not completely removed by conventional wastewater treatment technologies, such as physical, chemical, or biological treatment, because they are difficult to break down. Common CECs are personal care products, industrial chemicals, pharmaceuticals, pesticides, and synthetic organic chemicals, including endocrine disrupting chemicals, found in today's society. After being consumed and disposed, wastewater enters municipal sewerage systems and is released into rivers, lakes, groundwater, and other waters via treated or untreated wastewater effluents. The majority of CECs are typically found at levels less than $1 \text{ } \mu\text{g L}^{-1}$, but chronic exposure to these trace contaminants can also be significant and have adverse impacts on aquatic organisms (Cacace et al., 2019; Reid et al., 2019).

CECs can enter drinking water resources from the environment through bioaccumulation and transformation to potentially more toxic intermediates, potentially presenting risks to the ecosystem and human health when exposed to the environment over time. Therefore, the design of effective technologies that can remove these endowing pollutants has become a major research agenda.

As wastewater treatment technologies, advanced oxidation processes (AOPs) have been developed as potential methods to purify water by mineralizing various organic contaminants (Miklos et al., 2018). During oxidation reactions, in situ generated hydroxyl radicals ($\bullet\text{OH}$) and superoxide radicals ($\text{O}_2\bullet^-$) have very high oxidation potentials, allowing rapid destruction of recalcitrant organic molecules. UV, O_3 , and photocatalytic oxidation with semiconductor materials (TiO_2) and the Fenton-based oxidation systems are among the technologies that have proved to be very efficient for wastewater treatment applications (Liu et al., 2018; Rueda-Marquez et al., 2020; Serra et al., 2021; Zhang et al., 2019). However, most of these technologies are complex and require continuous external energy input or chemical additives, which further adds to the operating and treatment costs.

In recent years, due to its two-dimensional layered structure, high electrical conductivity, rich surface functional groups ($-\text{OH}$, $-\text{O}$, and $-\text{F}$), high hydrophilicity, and large specific surface area, MXene materials have attracted considerable attention as functional materials for membrane functionalization. These properties affect the membrane's water permeability, electron transport speed, high organic pollutant adsorption capacity, and good antifouling performance (Rueda-Marquez et al., 2020; Serra et al., 2021).

However, pristine MXene is prone to oxidation and can have low catalytic activity for extended periods. These limitations are overcome by combining TiO_2 nanoparticles with MXene nanosheets. The structural stability of MXene is enhanced, reducing the tendency for nanosheet restacking, increasing the number of catalytically active sites, increasing reactive oxygen species generation, promoting charge separation, and accelerating charge transfer at the composite interface. As such, the MXene- TiO_2 heterostructure possesses much better catalytic activity, ability to degrade pollutants, membrane durability, and self-cleaning properties than a membrane with an MXene or TiO_2 layer (Chen et al., 2018, 2019; Paul et al., 2023; Tummino et al., 2017).

In addition to the selective transport of molecules, the MXene- TiO_2 composite has the added advantage of simultaneously enhancing contaminant rejection, preventing membrane fouling, and enhancing membrane service life through the presence of catalytic degradation of the organic contaminants retained on the membrane surface (Chen et al., 2019; Janowska et al., 2020).

When combined with catalytic oxidation processes, membrane separation technologies are effective in removing organic micropollutants from water and wastewater. Nanofiltration (NF) membranes can be used for the selective removal of organic compounds and multivalent ions, making them potential alternatives to reverse osmosis (RO) systems operating under relatively low pressures. The combination of catalytic material and membrane separation technologies to ensure simultaneous pollutant rejection and catalytic degradation has been the subject of recent research (Janowska et al., 2021; Ma et al., 2020). These catalytic membranes have the properties of both physical separation and chemical oxidation, thereby enhancing the treatment efficiency and reducing the need for catalyst recovery (Boffa, 2020).

Various catalytic NF membranes have been developed by attaching a photocatalyst (Chen et al., 2020; Koe et al., 2020) or a functional biomolecule such as an enzyme on the membrane surface (Wang et al., 2017; Zhang et al., 2021a). Such hybrid systems provide enhanced degradation capabilities based on synergistic interactions between the catalyst components and matrixes and enhance operational stability while retaining the catalyst.

Graphene oxide (GO) membranes containing TiO_2 nanoparticles have been found to have excellent photocatalytic properties for water purification (Cesano et al., 2021; Du et al., 2020; Gopinath et al., 2020; Han et al., 2022; Karaolia et al., 2018; Liu et al., 2021; Qu et al., 2022; Rafique et al., 2023; Tran et al., 2020; Yang et al., 2020; Zhang et al., 2021b). GO/ TiO_2 is

a synergistic system that utilizes visible light, reduces the electron-hole recombination process, and increases the adsorption of pollutants on the catalytic active sites near the surface of the system, which is expected to improve the pollutant degradation efficiency. Furthermore, the continuous generation of ROS on membrane surfaces can help break down organic foulants that have settled on the surfaces and offer self-cleaning effect to lengthen the membrane operating time between cleaning cycles.

However, photocatalytic membranes may not be as efficient when water is highly turbid because of the reduced light penetration and photocatalytic activation caused by the suspended particles. Likewise, continuous operation might lead to the long-term instability of enzyme-functionalized membranes as a result of enzyme denaturation and loss of activity (Li et al., 2020). Hence, there is still a demand for catalytic membrane systems that can efficiently catalyze the degradation of pollutants without the use of external light irradiation or unstable biological catalysts.

Although significant improvements have been made in catalytic nanofiltration membranes, some key problems still need to be addressed. Most reported catalytic membranes utilize UV or visible-light activation for the catalytic process, and enzyme-functionalized membranes are susceptible to catalyst instability and loss of catalytic activity over time. In addition, many catalytic membrane systems lack integration of pollutant separation, catalytic degradation, and antifouling capability in a single membrane architecture. Thus, the development of multifunctional catalytic membranes that can effectively remove contaminants under mild operating conditions (without the need for external irradiation or chemical oxidants) remains an important research goal.

In this study, we present a multifunctional MXene-TiO₂/GO/HAL nanofiltration membrane composed of thermally active nanocomposites of MXene-TiO₂ nanoparticles embedded in a humic acid-like (HAL) crosslinked graphene oxide network on a commercially available polyethersulfone (PES) support. The obtained membrane has the advantages of molecular sieving and thermocatalytic degradation, which cannot be achieved by conventional photocatalytic membranes, as well as antifouling and dark self-cleaning properties. Bisphenol A (BPA) was chosen as a model contaminant to evaluate the membrane, and the membrane's filtration efficiency, catalytic degradation performance, fouling resistance, and environmental safety were systematically investigated.

2. Materials and Methods

2.1 Materials

Graphite powder, bisphenol A (BPA), and other analytical-grade chemicals were purchased from Sigma-Aldrich (St. Louis, MO, USA). Titanium aluminum carbide (Ti₃AlC₂ MAX phase) was obtained from Laizhou Kai Kai Ceramic Materials Co., Ltd. (China). Commercial polyethersulfone (PES) ultrafiltration membranes were supplied by Sorengy Co. (China). ACEA Pinerolese Industriale S.p.A. (Pinerolo, Italy) supplied the mature green compost (MGC) used to prepare the humic acid-like (HAL) crosslinker. Secondary effluent was collected from an urban wastewater treatment plant in Aalborg, Denmark. Data were processed using OriginPro 2021.

2.2 MXene synthesis

Selective etching of the Al layer from Ti₃AlC₂ MAX-phase powder in an aqueous LiF/HCl solution produced MXene nanosheets. The mixture was stirred for 24 h at 35 °C, after which the etched material was repeatedly washed with deionized water and centrifuged until the supernatant reached approximately pH 6. The resulting multilayer MXene was delaminated by ultrasonication under an inert atmosphere and collected by centrifugation.

2.3 Preparation of TiO₂ Nanoparticle Dispersion

Titanium dioxide (TiO₂) nanoparticles (Sigma-Aldrich, St. Louis, MO, USA) were dispersed in deionized water (18 M Ω · cm) at 10 g L⁻¹. The suspension was ultrasonicated for 30 min to obtain a homogeneous dispersion.

2.4 Preparation of the GO Dispersion

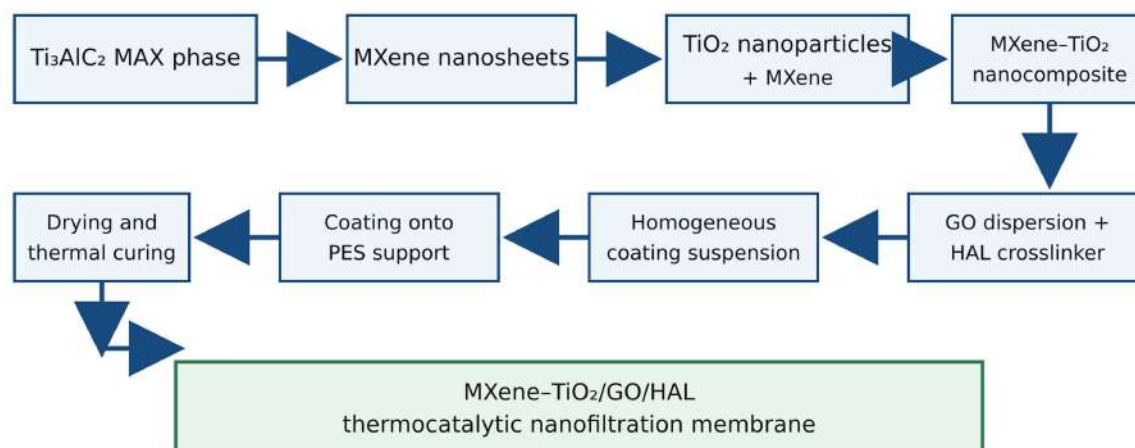
Graphene oxide (GO) was prepared using a modified Hummers method. Concentrated sulfuric acid (50 mL, 98%) was added to 1 g sodium nitrate and 2 g natural graphite under stirring in an ice bath. Potassium permanganate was then added gradually while the temperature was kept below 20 °C. After oxidation, the mixture was diluted with deionized water, treated with hydrogen peroxide, washed to near-neutral pH, and exfoliated by ultrasonication to obtain a stable GO dispersion.

2.5 Preparation of Humic Acid-Like (HAL) Crosslinker Solution

The HAL crosslinker was extracted from MGC following previously reported procedures (Beretta et al., 2026; Gao et al., 2019). Briefly, MGC was treated with alkaline solution, and the soluble humic fraction was separated, purified, and adjusted to the concentration required for membrane fabrication.

2.6 Fabrication of Membranes

Commercial PES ultrafiltration membranes (Sorengy Co., China) served as porous supports. The supports were washed with deionized water and dried before coating. MXene–TiO₂, GO, and HAL dispersions were mixed at the selected ratios, homogenized, deposited on the PES surface, dried, and thermally cured to form the catalytic nanofiltration layer (Scheme 1).



Scheme 1 Fabrication procedure for the MXene–TiO₂/GO/HAL thermocatalytic nanofiltration membrane

2.7 Thermocatalytic abatement tests and water analysis

Thermocatalytic BPA-abatement tests were conducted under reflux in the dark. A 500 mL BPA solution was heated to 50 °C in an oil bath, and a defined mass of catalyst was added under continuous stirring. Aliquots were collected at predetermined intervals, filtered, and analyzed by high-performance liquid chromatography. Apparent pseudo-first-order rate constants were obtained from the linear relationship between $\ln(C/C_0)$ and reaction time.

2.8 Filtration tests

Crossflow filtration was conducted with flat-sheet membranes (effective area 25 cm^2) using the laboratory system shown in Figure 1. Membrane selectivity was calculated from the BPA concentrations in the feed and permeate according to Equation (1).

$$\text{selectivity} = 1 - \frac{C_{\text{permeate}}}{C_{\text{feed}}} \quad (1)$$

The setup comprised a feed tank maintained at 50°C , a high-pressure feed pump, a rotary-lobe circulation pump, a flat-sheet nanofiltration module, inlet and outlet pressure transmitters, and a balance for continuous permeate-flow measurement. Tests used 1.8 L feed, 5 bar transmembrane pressure, and an approximate crossflow velocity of $4 \times 10^{-6} \text{ m s}^{-1}$. Feed and permeate samples were collected periodically for BPA analysis.

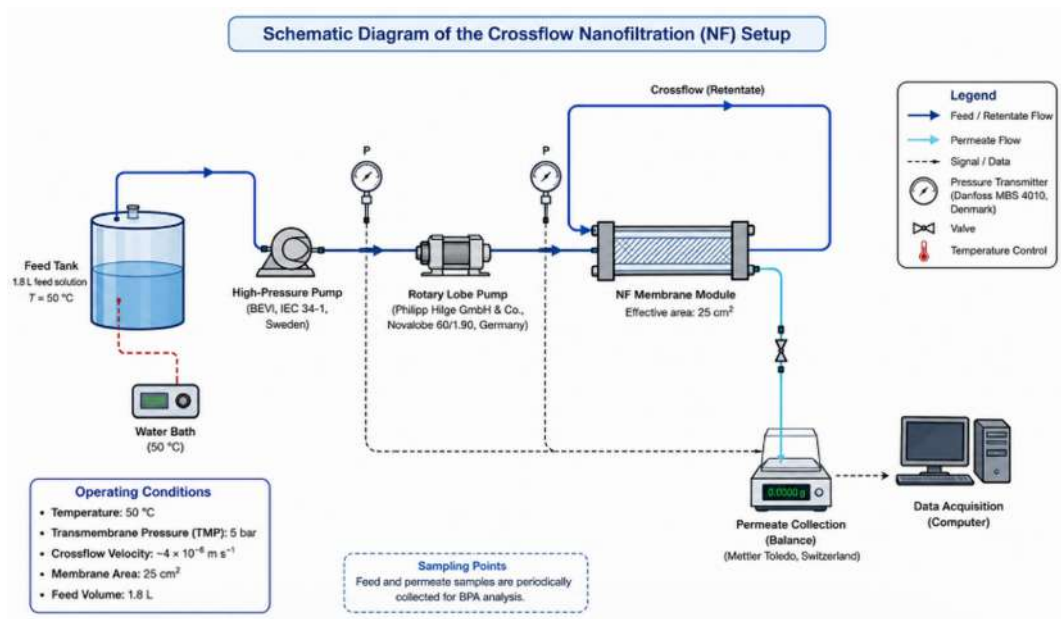


Figure 1 Laboratory-scale crossflow nanofiltration system used to evaluate membrane performance

2.9 Toxicological Effect Tests

Potential aquatic effects of released MXene–TiO₂ particles were assessed using three model organisms: the bioluminescent bacterium *Aliivibrio fischeri*, the freshwater alga *Raphidocelis subcapitata*, and the cladoceran *Daphnia magna*. Aqueous nanocomposite dispersions were prepared with a Sonica Q55 ultrasonic processor. The *A. fischeri* assay used eight replicates at 10 concentrations, and bioluminescence inhibition was measured after 30 min with a Victor X2 multilabel plate reader following a procedure adapted from Papagiannaki et al. (2020).

The *R. subcapitata* growth-inhibition assay used eight replicates at 10 concentrations in transparent 96-well microplates. Plates were agitated at 40 rpm under approximately 6500 lux, and growth was quantified by absorbance with a Multiskan plate reader. *D. magna* acute-immobility and starvation-survival tests followed Nielsen and Roslev (2018). One organism was placed in each well of a 24-well plate containing 2 mL test solution ($n = 24$) and exposed in the dark to three nanocomposite concentrations. Acute immobility was assessed after 24 or 48 h, and starvation survival was monitored until all organisms were immobile.

$$I = 1 - (R_i / R_c) \quad (2)$$

where R_i and R_c are the measured responses of the inhibited and control samples, respectively.

The concentration–response curves were fitted using a log-logistic model through iterative nonlinear regression (Equation 3).

$$\text{Response} = A_1 + \frac{A_2 - A_1}{1 + 10^{(\log x - c)p}} \quad (3)$$

where A_1 and A_2 are the lower and upper asymptotes, respectively; X is the median effective concentration (EC_{50}); C is the MXene–TiO₂ concentration (mg L^{-1}); and p is the model slope parameter.

A sigmoidal survival model was fitted by nonlinear regression to estimate the median starvation-survival time (SS_{50}) of *D. magna*, as described by Nielsen and Roslev (2018).

3. Results and Discussion

3.1 MXene–TiO₂ nanocomposites

Figure 2a presents the X-ray diffraction patterns of the individual components and selected MXene–TiO₂/GO/HAL nanocomposites. GO showed a characteristic peak at 11.33° (2θ), corresponding to an interlayer spacing of $7.79 \text{ \AA}$ and an O/C ratio of 0.27. The diffraction features of the catalytic phase remained visible in the composites, confirming successful incorporation into the GO–HAL matrix.

The addition of MXene–TiO₂ preserved the layered GO–HAL structure while introducing intimate contact between the catalytic particles and the carbonaceous matrix. High-resolution TEM images (Figure 2b–d) show GO nanosheets, the crosslinked GO–HAL matrix, and MXene–TiO₂ domains distributed within MTG-98.6.

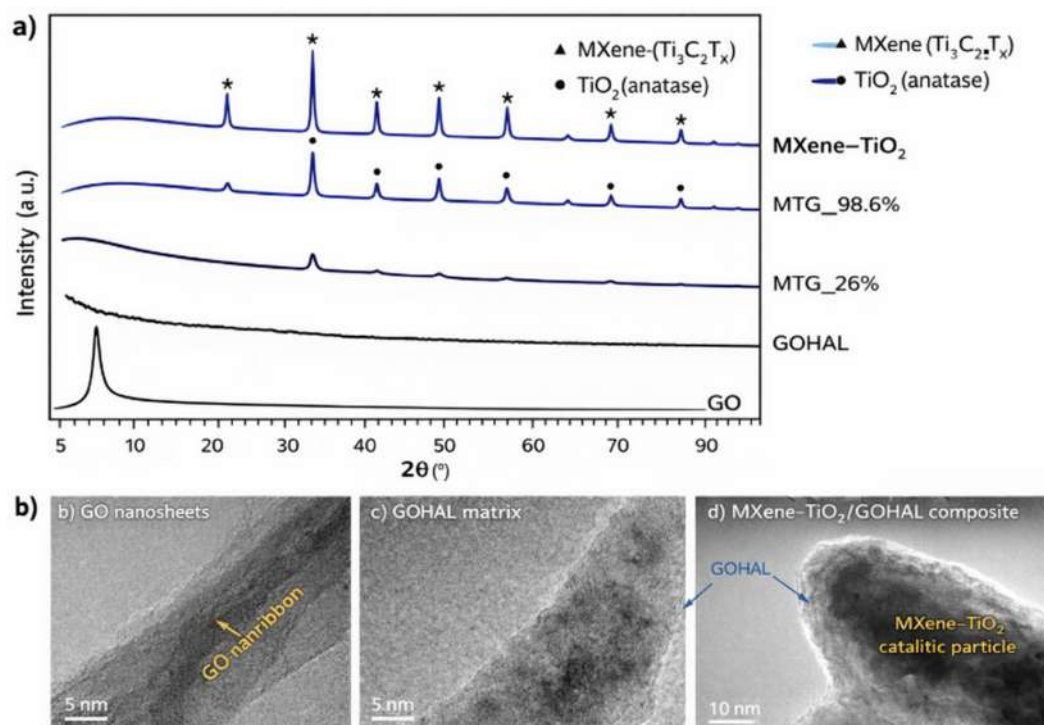


Figure 2 Structural and morphological characterization: (a) XRD patterns of GO, GO–HAL, MXene, MXene–TiO₂, and selected MXene–TiO₂/GO/HAL nanocomposites; (b) HR-TEM image of GO nanosheets; (c) HR-TEM image of the GO–HAL matrix; and (d) HR-TEM image of the MTG-98.6 composite

3.2 MXene–TiO₂/GO synergism in bisphenol A removal

Preliminary formulation tests optimized MXene–TiO₂ loading for catalytic activity and membrane-forming stability. The selected compositions therefore represent practical formulations rather than evenly spaced concentrations.

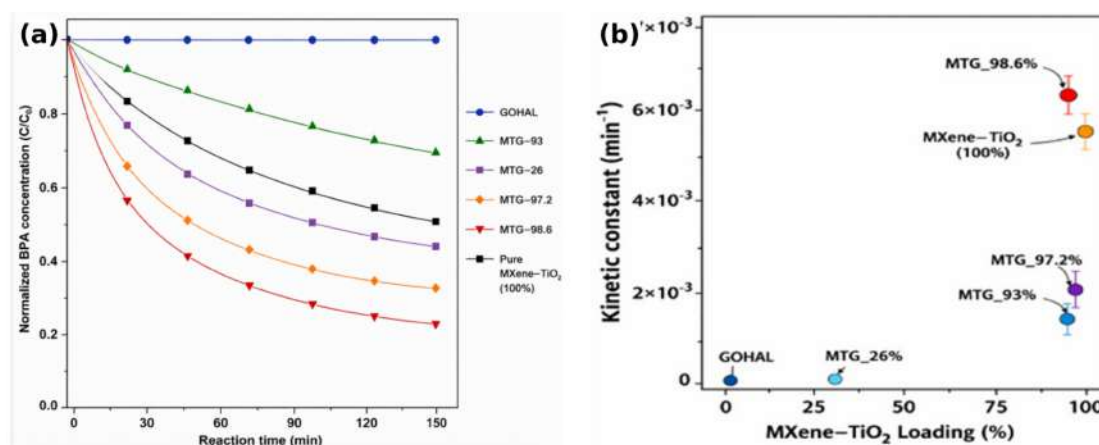


Figure 3 Thermocatalytic BPA degradation by MXene–TiO₂/GO/HAL nanocomposites: (a) normalized BPA concentration as a function of reaction time; and (b) apparent pseudo-first-order rate constant as a function of MXene–TiO₂ loading

MTG-98.6 exhibited the highest apparent rate constant, $(6.2 \pm 0.3) \times 10^{-3} \text{ min}^{-1}$, compared with $(5.2 \pm 0.1) \times 10^{-3} \text{ min}^{-1}$ for the unsupported catalytic phase.

As catalytic loading decreased, the apparent rate constants were $(1.89 \pm 0.08) \times 10^{-3} \text{ min}^{-1}$ for MTG-97.2%, $(1.72 \pm 0.05) \times 10^{-3} \text{ min}^{-1}$ for MTG-93%, and $(1.6 \pm 0.9) \times 10^{-4} \text{ min}^{-1}$ for MTG-26%.

This trend indicates that, despite a favorable interaction between GO–HAL and the catalytic phase, excess GO–HAL can partially cover MXene–TiO₂ particles and restrict access to active sites.

The rate constant of degradation of BPA using MTG (98.6%) in the dark at 50 °C is similar to the values obtained when TiO₂ is used as a photocatalyst under light irradiation (Fu et al., 2022; Garg et al., 2019; Hunge et al., 2021; Wu et al., 2020).

3.3 MXene–TiO₂ nanofiltration membranes

Because MTG-98.6 showed the highest BPA-degradation activity, it was selected to fabricate the catalytic nanofiltration membrane on a commercial PES ultrafiltration support. The coating formed a continuous active layer across the membrane surface (Figure 4).

EDS analysis identified the GO–HAL-rich region (α) as predominantly carbon and oxygen (C = $72.67 \pm 8.21 \text{ at.}\%$; O = $23.43 \pm 9.58 \text{ at.}\%$). Ti and O signals in region β confirmed the presence of the MXene–TiO₂ catalytic phase.

3.4 Rejection and Abatement of Bisphenol A by MXene–TiO₂ Nanofiltration Membranes

Crossflow tests compared the pristine PES support, the GO–HAL reference, and the MTG-98.6 membrane (Figure 5a). Pristine PES showed the highest water permeance because it lacked a selective coating. GO–HAL and MTG-98.6 exhibited permeances of approximately 0.8 and 1.3 L m⁻² h⁻¹ bar⁻¹, respectively. This result indicates that incorporating MXene–TiO₂ within the GO–HAL matrix contributes additional water-transport pathways while preserving the catalytic functionality of the membrane surface.

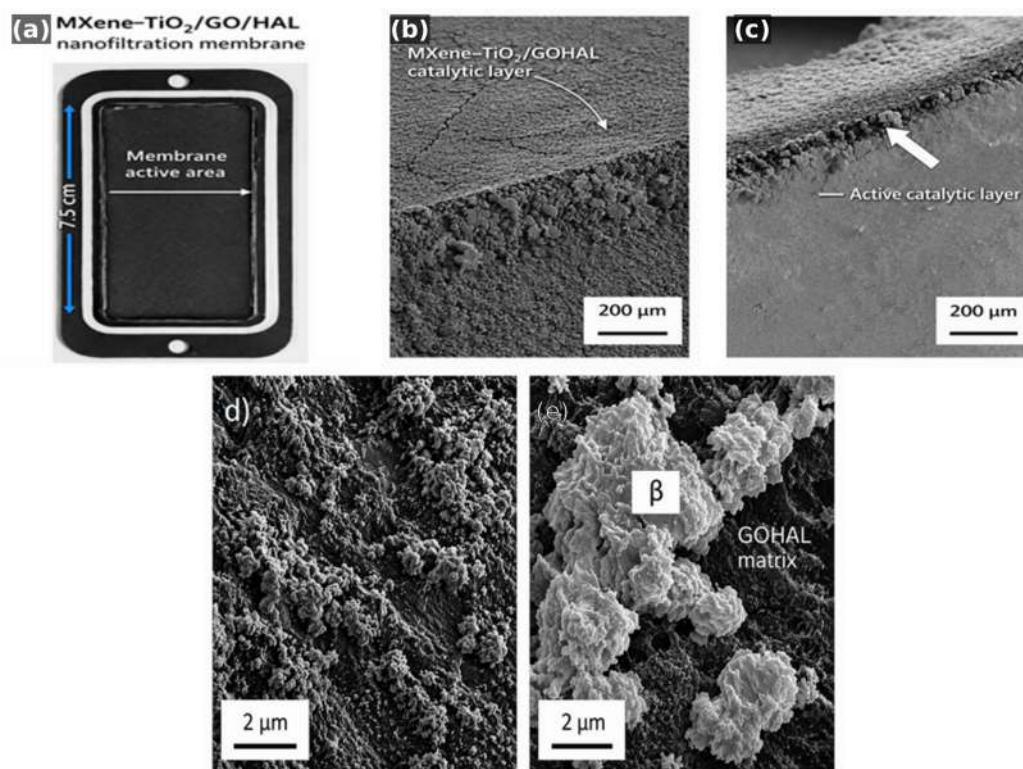


Figure 4 Morphology of the MXene-TiO₂/GO/HAL nanofiltration membrane: (a) photograph of the membrane coated on a PES support (length 7.5 cm); (b) SEM image of the membrane surface showing the continuous MXene-TiO₂/GO-HAL catalytic layer; (c) cross-sectional SEM image showing the thin active catalytic nanofiltration layer supported on the PES substrate; (d) high-magnification SEM image of MXene-TiO₂ particles within the GO-HAL matrix; and (e) interface between the GO-HAL matrix (α) and MXene-TiO₂ catalytic phase (β)

GO sheets generally align parallel to the membrane surface and create tortuous pathways for water transport. In the MXene-TiO₂/GO-HAL composite, the carbonaceous sheets are distributed around MXene-TiO₂ particles (Figure 2d), producing more varied channel orientations and lower transport tortuosity. BPA filtration was therefore evaluated with a 10 mg L⁻¹ feed at 50 °C under continuous crossflow (Figure 5b).

During 18 h of crossflow filtration, the BPA concentration in the MTG-98.6 feed decreased from 10.19 ± 0.03 to approximately 4.1 mg L⁻¹, whereas the permeate concentration remained 0.33 ± 0.09 mg L⁻¹ (Figure 5b). The GO-HAL membrane retained BPA but did not produce a comparable decrease in feed concentration, confirming the contribution of thermocatalytic degradation.

The reproducibility of membrane fabrication was determined by testing three independently prepared MTG-98.6 membranes under the same conditions.

As demonstrated in Figure 5b, the three membranes exhibited simultaneous retention and degradation of BPA, indicating the simultaneous exertion of selective and thermocatalytic functions of the active layer.

$$y = (9.9 \pm 0.1) \exp \{(-0.027 \pm 0.002)x\} \quad (4)$$

The concentration profiles show excellent agreement, which demonstrates the reproducibility of the coating method and the high BPA selectivity of MTG-98.6.

According to Equation (1), BPA rejection decreased slightly from approximately 97% to 94%, which is probably due to BPA adsorption, concentration polarization, and slow surface fouling.

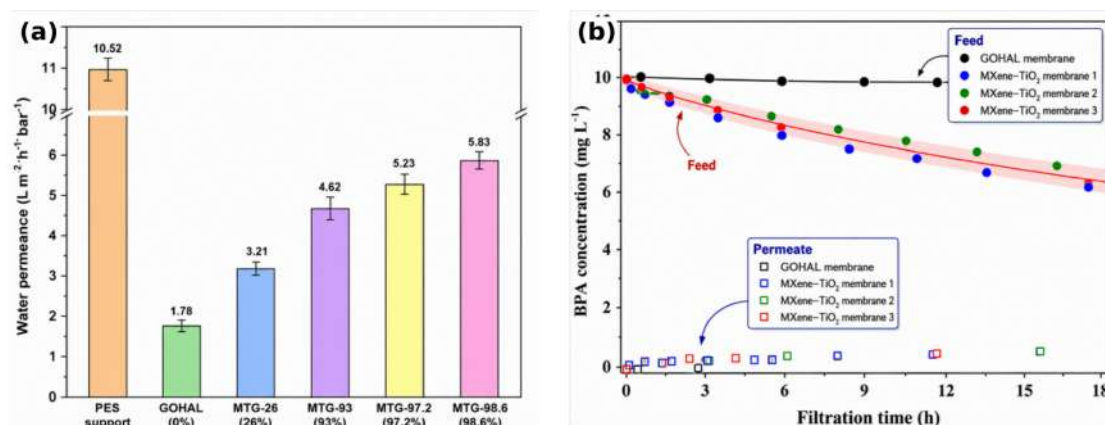


Figure 5 Nanofiltration performance: (a) water permeance of the PES support, GO–HAL reference, and MXene–TiO₂/GO/HAL membranes; and (b) BPA concentrations in the feed and permeate during crossflow tests with the GO–HAL membrane and three independently prepared MTG-98.6 membranes

3.5 Antifouling properties

Urban wastewater-treatment-plant effluent was filtered through MTG-98.6 and the GO–HAL reference to assess organic-matter removal and fouling. Both membranes showed time-dependent flux decline, but MTG-98.6 stabilized at a higher long-term flux (Figure 6a). After 12 h, the normalized TOC in the retentate decreased to approximately 0.25 for MTG-98.6 and 0.46 for GO–HAL (Figure 6b), indicating enhanced removal by the catalytic membrane.

Permeate TOC remained lower for MTG-98.6 (approximately $0.18 C_{\text{permeate}}/C_{\text{feed}}$) than for GO–HAL (approximately 0.45–0.53) throughout the test (Figure 6c). This behavior indicates that thermocatalysis and adsorption supplemented size exclusion and helped limit organic fouling.

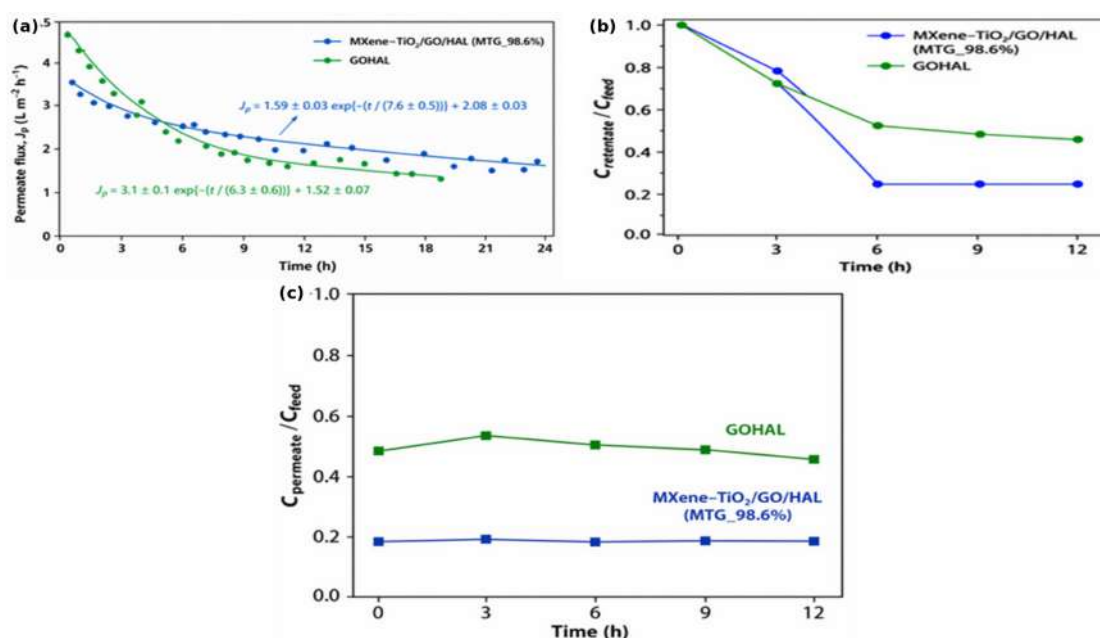


Figure 6 Filtration of wastewater-treatment-plant effluent using MTG-98.6 and the GO–HAL reference: (a) permeate flux as a function of time; (b) normalized feed TOC; and (c) normalized permeate TOC

XPS survey spectra were collected before and after 24 h of filtration to assess changes in membrane-surface chemistry (Figure 7). After filtration, both membranes showed additional N and Ca signals associated with retained wastewater constituents. The N1s peak at 400 eV, a

characteristic value for organic nitrogen species, confirmed this fouling.

The survey spectra confirm that both membranes retained organic and inorganic wastewater constituents. Differences in the N/Ca atomic ratio (3.6 for GO–HAL and 2.8 for MTG-98.6) further indicate distinct foulant accumulation on the two surfaces. The Ti 2p signals in the MTG-98.6 survey spectrum (Figure 7b) confirm incorporation and retention of the MXene–TiO₂ catalytic phase during filtration. High-resolution C1s spectra of GO–HAL and MTG-98.6 (Figure 7c,d) were deconvoluted into graphitic carbon (C–C/C–H) at 284.6 eV, oxygenated carbon (C–OH/C–O–C) at approximately 286.2 eV, and carbonyl/carboxyl species (C=O/O–C=O) at higher binding energy. After 24 h, shifts in component intensities indicated foulant interactions and modest surface chemical changes. MTG-98.6 retained the spectral features of its catalytic layer, supporting its chemical stability under the test conditions.

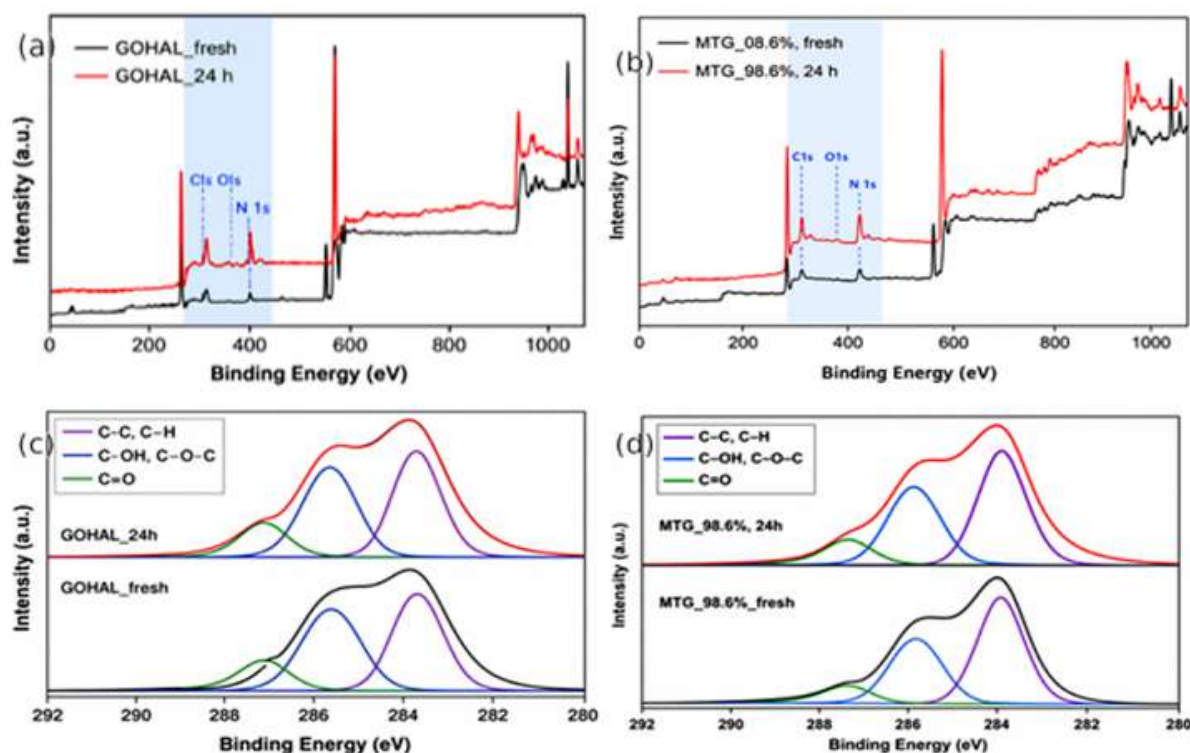


Figure 7 XPS characterization before and after 24 h of filtration: survey spectra of (a) GO–HAL and (b) MTG-98.6 membranes, and high-resolution C1s spectra of (c) GO–HAL and (d) MTG-98.6 membranes

Comparison of the C1s component distributions showed a decrease in the C–OH/C–O–C fraction after filtration, consistent with interactions between retained organic matter and oxygenated surface groups. The MTG-98.6 spectrum nevertheless retained the characteristic carbon components of the GO–HAL matrix (Park & Lee, 2022; Suhaimin et al., 2022).

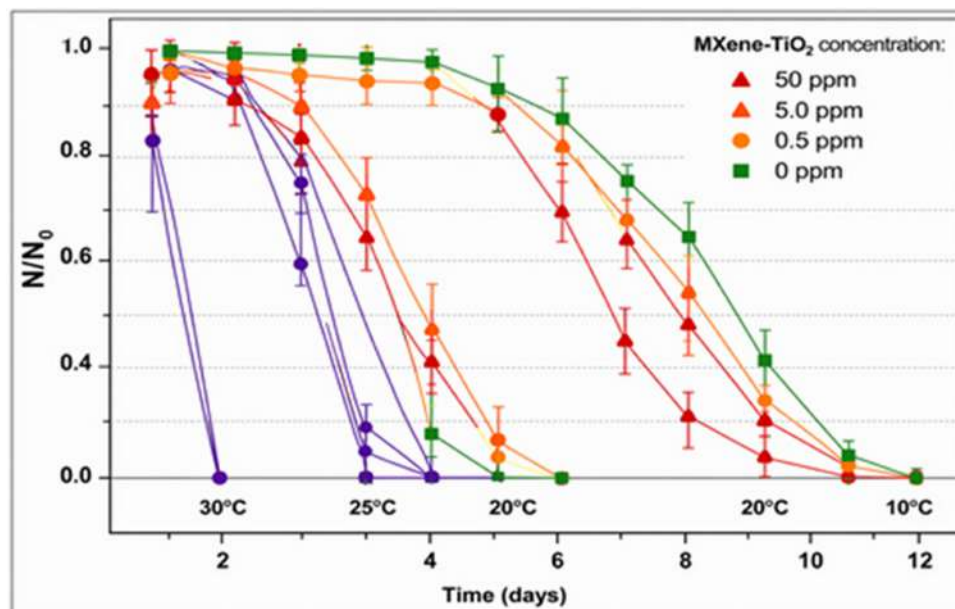
3.6 Toxicology of aquatic model organisms

Table 1 summarizes the acute ecotoxicity of MXene–TiO₂ toward three aquatic model organisms. The EC₅₀ values exceeded 10 mg L^{−1} for all organisms, indicating low acute toxicity under the UN Globally Harmonized System. *A. fischeri* showed EC₂₀ = 62.4 mg L^{−1} and EC₅₀ > 105 mg L^{−1}, *R. subcapitata* showed EC₂₀ = 21.3 mg L^{−1} and EC₅₀ > 55 mg L^{−1}, and *D. magna* showed EC₂₀ > 52 mg L^{−1} and EC₅₀ > 58 mg L^{−1}.

Additional *D. magna* experiments evaluated survival at MXene–TiO₂ concentrations of 0.5, 5, and 50 mg L^{−1} and incubation temperatures of 10, 20, 25, and 30 °C (Figure 8). Figure 8 shows concentration- and temperature-dependent *D. magna* survival. Controls retained the highest survival, whereas increasing MXene–TiO₂ concentration progressively shortened survival.

Table 1 Acute ecotoxicity of the MXene–TiO₂ nanocomposite at 20 °C

Organism	Exposure Time	EC ₂₀ (mg L ⁻¹)	EC ₅₀ (mg L ⁻¹)
<i>Aliivibrio fischeri</i>	30 min	62.4	>105
<i>Raphidocelis subcapitata</i>	72 h	21.3	>55
<i>Daphnia magna</i>	48 h	>52	>58

**Figure 8** Survival of *Daphnia magna* exposed to MXene–TiO₂ nanocomposite at 0, 0.5, 5, and 50 mg L⁻¹ and incubation temperatures of 10, 20, 25, and 30 °C. N_t is the number of surviving organisms at time t , and N_0 is the initial number of organisms

At 50 mg L⁻¹, complete mortality occurred within a few days at 25 and 30 °C, whereas lower concentrations caused slower declines. Higher temperature hastened mortality, indicating that temperature amplified the effects of the nanocomposite. Preventing particle release and confirming long-term stability are therefore important for environmental deployment.

4. Conclusions

This study developed an MXene–TiO₂/GO–HAL active layer on a commercial PES support for combined nanofiltration and dark thermocatalytic treatment. MTG-98.6 delivered the highest BPA-degradation rate, increased water permeance relative to GO–HAL, and maintained high BPA rejection during 18 h of crossflow filtration. With real wastewater effluent, the catalytic membrane produced lower permeate TOC and a higher stabilized flux than the GO–HAL reference. XPS confirmed retention of the catalytic phase after filtration. Acute tests indicated low toxicity to *A. fischeri* and *R. subcapitata*, while *D. magna* survival decreased with increasing particle concentration and temperature. The membrane therefore offers a promising route to couple separation, contaminant degradation, and fouling mitigation using low-grade heat. Future work should quantify catalyst retention, transformation products, long-term hydraulic stability, and performance under continuous full-scale-relevant operation.

Conflict of Interest

The authors declare no conflicts of interest.

Declaration of AI

During manuscript preparation, generative artificial intelligence was used solely for English-language editing and formatting assistance. The authors reviewed and verified the final text and take full responsibility for the scientific content, interpretations, and conclusions.

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