

Synergistic MXene-silver Coatings for Advanced Antibacterial Nylon 6,6 Membranes

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Abstract

The growing threat of antibiotic-resistant pathogens necessitates the development of novel antibacterial materials. In this study, $\text{Ti}_3\text{C}_2\text{T}_x$ -based MXene and MXene-silver composite coated Nylon-6,6 membranes were fabricated and evaluated for their antimicrobial properties. Nylon 6,6 membranes were coated with MXene using a vacuum-assisted filtration technique to enhance surface functionality and antibacterial performance. To further improve antibacterial efficacy, silver (Ag) nanoparticles were incorporated into the MXene layer, forming MXene-silver composite materials. The X-ray diffraction analysis of MXene confirmed successful phase transformation, evidenced by a pronounced shift in the (002) peak corresponding to increased interlayer spacing and the formation of few-layered MXene. Scanning electron microscopy of the coated membranes revealed a uniformly distributed, wrinkled, layered morphology, indicating effective surface coverage and strong interaction with the membrane substrate. Fourier-transform infrared spectroscopy verified the presence of -OH, -F, and -O functional groups, confirming successful surface functionalization. Antibacterial assays demonstrated that both MXene and MXene-silver coated membranes exhibit significant inhibition of bacterial growth, with the highest antibacterial activity observed for membranes containing 2 wt.% silver incorporated MXene at a concentration of 0.06 mg/mL. This enhanced performance was attributed to the synergistic effects of MXene's reactive surface terminations and the bactericidal properties of silver. Overall, these findings demonstrate that MXene-silver composite coated membranes possess excellent structural, surface, and antibacterial characteristics, highlighting their potential for applications in antibacterial coatings, water purification, and biomedical filtration.

Keywords: MXene, Silver, MXene-silver, Nylon 6,6-Membrane, antibacterial, coatings

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1. Introduction

Recently, there has been a lot of interest in two-dimensional (2D) materials with extremely high aspect ratios and thicknesses that correspond to a few atomic layers [1-3]. Following the discovery of exceptional electrical characteristics of graphene, a lot of increased interest has been shown in materials such as metal oxides, transition metal dichalcogenides, hexagonal boron nitrides, and hydroxides [4-6]. MXenes are a novel and perhaps sizable class of early transition metal carbides and/or carbonitrides that have just joined the family of 2D materials [5]. MXenes have many merits including chemical active surface, tunable electric band gap, optical transparency, excellent mechanical properties and hydrophilic nature etc. [6]. These fascinating properties may lead to important applications and attracted much attention from researches in various fields such as energy storage, electromagnetic interference (EMI) shielding, sensors, photonics and biocompatible applications etc. [7-8]. Because of its excellent electrical conductivity and prospective electrochemical usefulness, MXene is gaining a lot of attention as a hybridization matrix for creating functional nanohybrids. Such unique physicochemical properties and economic merit of MXene nanosheet evoke great deal of research efforts on its hybridization with diverse inorganic solids [9-10]. MXenes, two-dimensional transition metal carbides/nitrides exhibit potent antibacterial activity through membrane disruption by sharp nanosheet edges, oxidative stress via ROS generation and enhanced photothermal/photodynamic effects under light. Since initial reports around 2016 research has explored pure MXene coatings and composites demonstrating >98 % bacterial killing in *E. coli* and *B. subtilis*, effective wound dressings and anti-biofouling membranes for water treatment [11-14]. Their large surface area, surface functional groups, excellent conductivity and biocompatibility enable multifunctional applications though challenges remain in material stability, toxicity, green synthesis and long-term biosafety [15]. Multiple antibacterial mechanisms were made possible by the surface chemistry and structural characteristics of MXenes [16]. Physical damage is one of the main ways that MXenes work against bacteria; the “nano-knife” effect is the term used to describe how the sharp edges of MXene nanosheets can puncture and damage bacterial cell membranes, allowing intracellular components to leak out and eventually causing cell death [13]. Furthermore, bacterial cells may experience oxidative stress due to their capacity to produce reactive oxygen species (ROS), which can harm proteins, DNA, and lipids, particularly when exposed to light or in particular environmental circumstances [17]. MXenes can also promote electron transfer reactions that disrupt the

respiratory functions of bacteria, making it harder for them to survive. Moreover, MXene's biocompatibility with mammalian cells makes them promising candidates for biomedical applications like wound dressings, antibacterial coatings and implantable devices [18]. Their antibacterial action is not merely due to passive interactions but can be tailored by modifying synthesis routes, terminal groups, flake size, and composite formation, offering tunable antibacterial properties [19]. $\text{Ti}_3\text{C}_2\text{T}_x$ doped membranes exhibited significant antibacterial performance by the hydrophilic functional groups (-OH) on MXene nanosheets improves adhesion to bacterial cell membranes via hydrogen bonding and forms a physical trapping effect that restricts the nutrient exchange required for bacterial proliferation [20,21]. Antibacterial property of $\text{Ti}_3\text{C}_2\text{T}_x@\text{PEI}/\text{Ag}$ membrane with high bactericidal efficiency can be used for the treatment of seawater [22-23]. The titanium dioxide produced by MXene oxidation has certain photothermal catalytic bactericidal effect composited with photothermal materials [24]. As MXenes can target and eliminate cancer cells or pathogens, research in this domain is progressing [25]. MXenes can be manipulated into many configurations including thin films and thick membranes due to its processing capability [26]. MXenes have the ability to eliminate malignant cells by a combination of photothermal ablation and chemotherapy, which is facilitated by their exceptional efficiency in converting light into heat [27]. Vacuum filtration of dispersions is a versatile method to form freestanding films or coated membranes whose thickness and porosity can be precisely tuned by adjusting the dispersion concentration and filtered volume. In practice, an aqueous or polar solvent dispersion of delaminated MXene flakes is poured onto a porous membrane under vacuum. As the solvent is drawn through, MXene nanosheets deposit in a face-to-face, densely packed arrangement due to capillary forces higher concentrations or larger volumes yield thicker films, while lower concentrations produce thinner, more porous layers. It involves filtering a dispersion of MXenes through a membrane, typically nylon 66, to form a thin membrane which influences the resulting membrane's properties [28]. The present study aimed to fabricate and characterize $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and MXene-silver composite coated Nylon 6,6 membranes with enhanced surface functionality and structural properties. Furthermore, the antibacterial performance of the coated membranes was evaluated to investigate the synergistic effect of MXene and silver nanoparticles on bacterial growth inhibition.

2. Experimental

2.1. Materials

The materials used in this study included Titanium Aluminium Carbide (Ti_3AlC_2 , MAX phase; Forsman, 98% purity, 200 mesh), Lithium Fluoride (LiF ; Alfa Aesar, 98.5%), Hydrochloric Acid (HCl ; Emparta, 35%), Ethanol (Hayman, UK) and Silver Nitrate (AgNO_3 ; Loba Chemie, extra pure grade). Deionized water (dH_2O) was used throughout the experimental procedures.

2.2. Preparation of MXene

$\text{Ti}_3\text{C}_2\text{T}_x$ based MXene was synthesized through the selective etching of the Al layer from Ti_3AlC_2 (MAX) using an in-situ HF etching method [29]. A predetermined amount of LiF was dissolved in 9 M HCl in a 100 mL PTFE bottle, followed by the gradual addition of Ti_3AlC_2 powder under continuous stirring at 45 °C for 24 h. The resulting product was washed repeatedly with deionized water and centrifuged at 10,000 rpm until the pH of the supernatant reached ≥ 6 , indicating the removal of residual etchants and reaction by-products.

The sediment was dispersed in deionized water and delaminated using probe sonication (EL-250UP) for 1 h, followed by repeated centrifugation cycles. To further enhance exfoliation, ethanol intercalation was performed in conjunction with sonication and centrifugation. The supernatant containing delaminated MXene nanosheets was collected in polypropylene bottles, and the process was repeated to maximize MXene yield. The obtained MXene dispersion was subsequently used for the fabrication of MXene-coated membranes via the vacuum assisted filtration (VAF) method.

2.3 Preparation of MXene and MXene-silver coated Nylon 6,6-membranes

MXene and MXene-silver coated Nylon 6,6-membranes were fabricated using the vacuum assisted filtration (VAF) method. MXene dispersions of varying concentrations (0.002, 0.008, 0.01, 0.02, 0.03, and 0.06 mg mL^{-1}) and silver powder loadings of 2, 3 and 4 wt.% relative to MXene were prepared separately [30]. An Ultipor Nylon 6,6-membrane (pore size: 0.45 μm) was mounted in the filtration set-up, and approximately 10 mL of each dispersion was vacuum-filtered through the membrane for 30 min, resulting in the deposition of MXene nanosheets onto the membrane surface. The resulting MXene-coated membranes were removed and dried in an oven at 60 °C for 30 min.

For the preparation of MXene-silver coated composite membranes, 20 mL of MXene dispersions at the desired concentrations were transferred to a beaker and the required amount

of silver powder was added. The mixture was ultrasonicated in an ultrasonic bath (Model LMUC-3, 2.5 L capacity, 40 kHz frequency) for 30 min to achieve a homogeneous dispersion. The ultrasonicated MXene-silver dispersion was then vacuum-filtered through the Nylon 6,6 membrane for 30 min to deposit the composite coating. The coated membranes were subsequently removed and dried at 60 °C for 30 min. Using this procedure, Nylon 6,6 membranes with different MXene and MXene-silver loadings were successfully fabricated and stored for further characterization and antibacterial studies.

2.4. Material Characterization

The crystalline structure of the prepared materials was analysed using powder X-ray diffraction (XRD) (Rigaku Miniflex) with CuK α radiation. Diffraction patterns were recorded at a scanning rate of 3° min⁻¹ under operating conditions of 40 kV and 15 mA, and the obtained data were compared with standard JCPDS reference patterns. Thermogravimetric analysis coupled with differential scanning calorimetry (TGA-DSC) was performed using a TA Instruments SDT Q600 under a nitrogen atmosphere to evaluate the thermal stability and decomposition behaviour of the samples. Fourier-transform infrared (FT-IR) spectra were acquired using a Perkin Elmer Spectrum Two FT-IR spectrometer to identify the surface functional groups present in the materials. The surface morphology and elemental composition of the fabricated membranes were examined by Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDAX), respectively, with a Carl Zeiss EVO18 scanning electron microscope equipped with an EDAX detector.

2.5. Antibacterial property analysis

The antibacterial activity of the fabricated MXene and MXene-silver coated Nylon 6,6 membranes was evaluated using the agar disc diffusion method against Gram-positive bacteria, namely *Staphylococcus aureus* (*S. aureus*, ATCC 6538) and *Enterococcus faecalis* (*E. faecalis*, ATCC 29212) and *Escherichia coli* (*E. coli*, ATCC 25922) as well as Gram-negative bacteria, *Pseudomonas aeruginosa* (ATCC 27853) (Gram-negative) under aseptic conditions. Discs prepared from the fabricated membranes were surface-sterilized under UV light for 30 minutes prior to testing. A single isolated bacterial colony was inoculated into 10 mL of nutrient broth and incubated overnight at 37°C. The resulting bacterial suspension was uniformly spread onto sterile Muller-Hinton-Agar (MHA) plates using a sterile cotton swab. Sterile wells then created using a well borer, and the test samples dispersion in ethanol were introduced into the wells along with appropriate control samples. The prepared membrane

discs were also placed on the inoculated agar surface. The plates were subsequently incubated at 37 °C for 24 h. Following incubation, antibacterial activity was assessed by observing the formation of clear zones of inhibition around the wells and membrane discs, and the diameters of the inhibition zones were measured in centimetres.

3. Results and Discussion

Figure 1 presents the images of the fabricated MXene and MXene-silver coated Nylon 6,6 membranes.

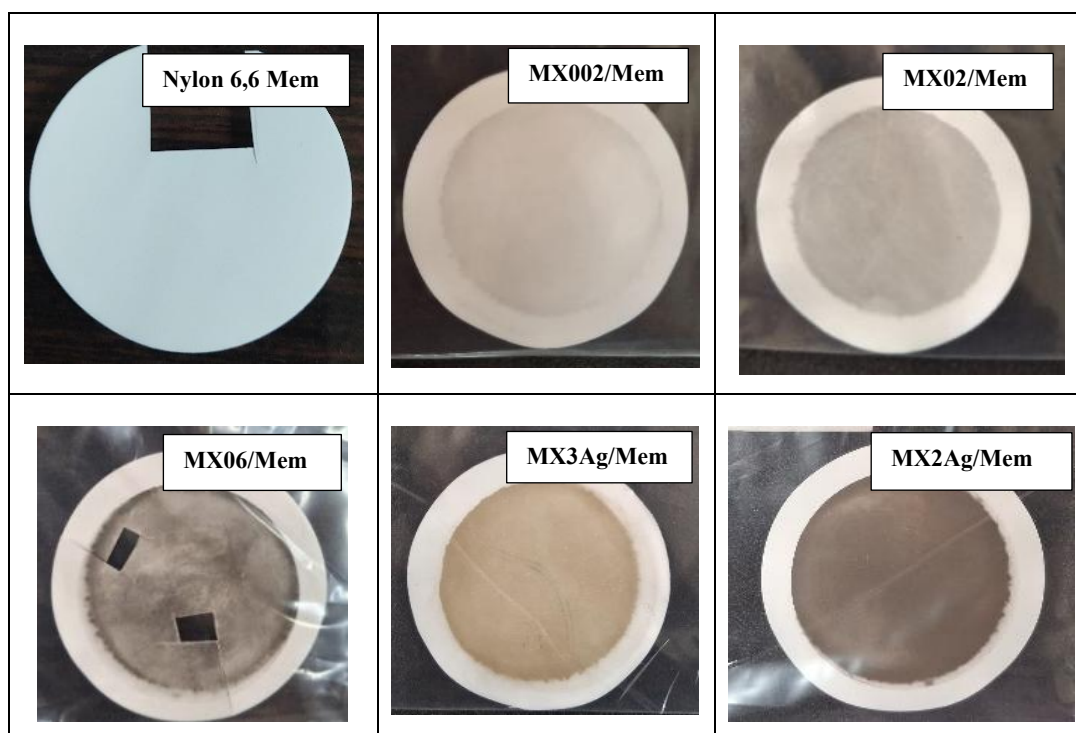


Figure 1. The images MXene and MXene-silver coated Nylon 6,6-membranes

The lower MXene-coated membranes (MX002/Mem and MX02/Mem) exhibit a relatively uniform light grey coating, indicating successful deposition of the MXene layer over the membrane surface. As the MXene content increases, the high-MXene-content membrane (MX06/Mem) displays a darker grey appearance with a thicker and denser coating, confirming greater MXene deposition. However, the coating becomes slightly non-uniform with the presence of agglomerated regions, suggesting that excessive MXene loading may promote particle aggregation while still providing a highly conductive surface with an increased number of active sites. In comparison, the MXene-silver composite-coated membranes (MX3Ag/Mem and MX2Ag/Mem) exhibit a more intense and uniformly

distributed dark grey coating, indicating the successful incorporation of silver nanoparticles within the MXene layer. The continuous coating with only minor edge variations suggests good adhesion and homogeneous dispersion of the conductive materials. The addition of silver enhances the coating density and surface coverage, which is expected to improve the electrical conductivity, surface activity, and overall performance of the membranes in sensing, filtration, and related applications.

Powder X-ray diffraction (XRD) analysis performed to examine the crystalline structure of the fabricated membranes. The XRD patterns are presented in Figure 2.

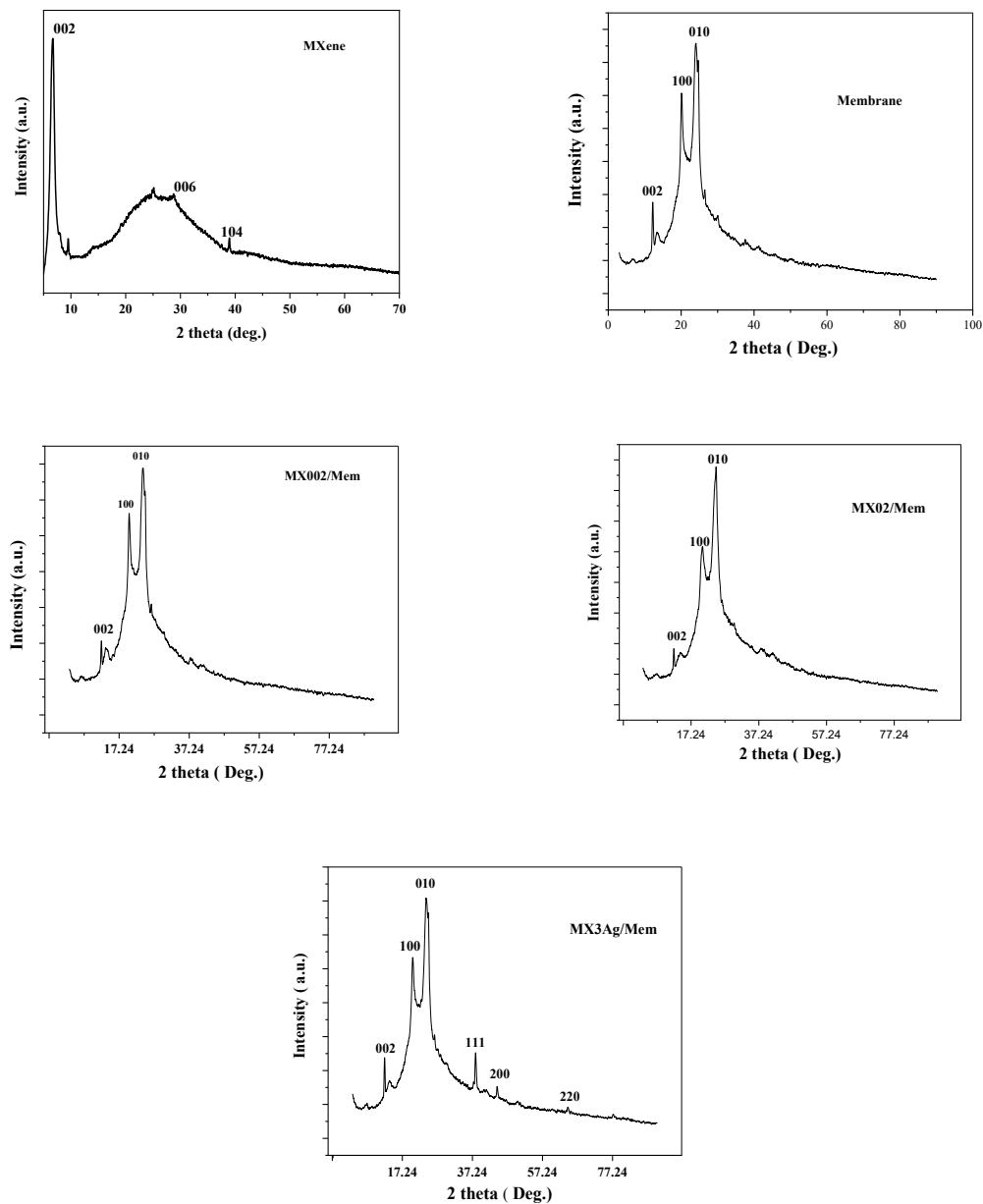
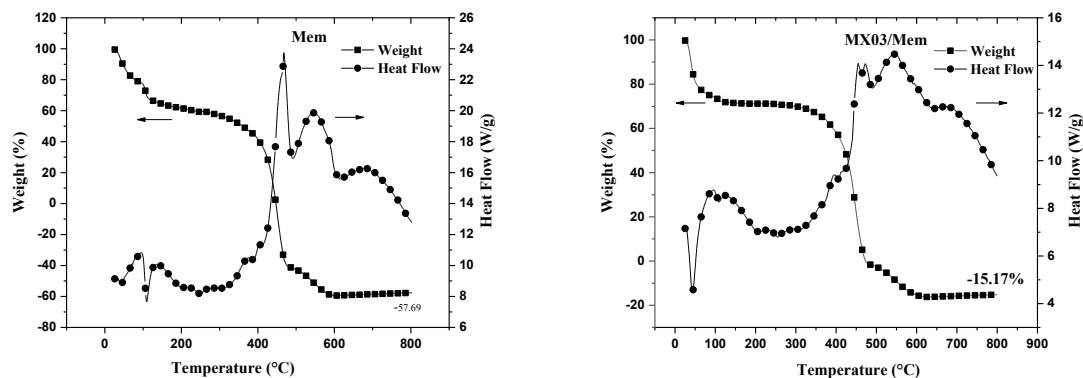


Figure 2. The X-ray diffraction patterns of the fabricated membranes

The XRD pattern of the synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene exhibits a prominent diffraction peak at $2\theta \approx 9^\circ$, corresponding to the (002) crystal plane. The strong (002) reflection and its shift to a lower diffraction angle compared to the parent MAX phase confirm the successful etching of the Al layer and the formation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene [31]. This shift indicates an increase in the interlayer spacing (d-spacing) due to the introduction of surface termination groups (-OH, -O, and -F) and the intercalation of water molecules between the MXene layers. Broad diffraction features observed around $2\theta \approx 28^\circ$ (006) and $\approx 39^\circ$ (104) are characteristic of multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and indicate the preservation of the layered structure after etching. The absence or significant reduction of the characteristic MAX phase peaks further confirms the successful conversion of the MAX phase into $\text{Ti}_3\text{C}_2\text{T}_x$ MXene with a well-exfoliated layered morphology [32].

The XRD pattern of Nylon 6,6-membrane displays distinct diffraction peaks at $2\theta = 20.2^\circ$ (100), 24.2° (010), and 12.2° (002), indicating the semicrystalline nature of membrane and confirming the presence of an ordered polymeric phase [33]. Upon coating with MXene (MX002/Mem and MX02/Mem) diffraction peaks corresponding to Nylon6,6-membrane are still observed at $2\theta = 20.2^\circ$ (1 00), 24.2° (010), and 12.2° (002). In the XRD patterns of the MXene-coated Nylon 6,6-membranes, no additional peaks corresponding to MXene are detected, which may be attributed to the low concentration of MXene on the membrane surface. In contrast, MXene-silver coated Nylon 6,6-membrane (MX-3Ag/Mem) exhibits additional diffraction peaks at $2\theta = 38.1^\circ$ (111), 44.3° (200), and 64.4° (220), corresponding to the face-centred cubic structure of metallic silver, thereby confirming the successful incorporation of Ag nanoparticles onto the MXene layer [34].

Thermogravimetric analysis-differential scanning calorimetry (TGA-DSC) was performed to investigate the thermal decomposition of the fabricated membranes. The TGA-DSC curves of MXene and MXene-Ag coated Nylon 6,6-membranes are shown in Figure 3.



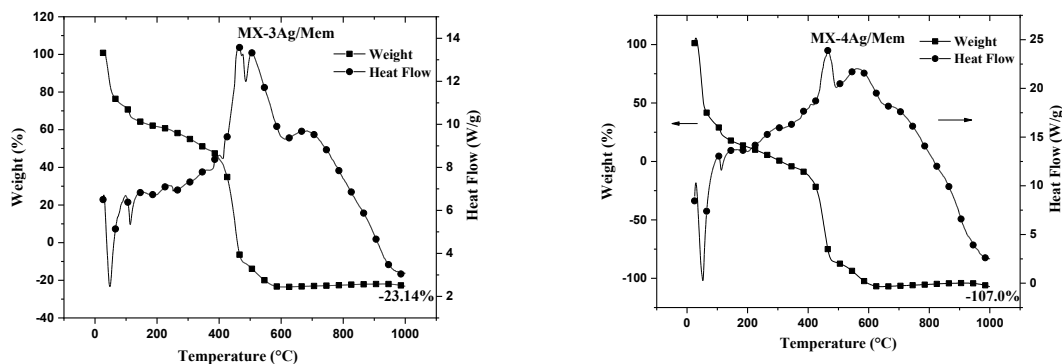


Figure 3. TG-DSC of fabricated membranes

The TGA-DSC analysis of the Nylon 6,6 membrane (Mem) shows an initial weight loss at ~ 108 °C due to moisture evaporation, followed by major thermal degradation at ~ 468 °C. The membrane remains thermally stable up to ~ 350 °C and exhibits a total weight loss of approximately 58%, leaving about 42% residue. Compared to the pristine membrane, the TGA-DSC profile of the MXene-coated nylon membrane MX03/Mem exhibits two exothermic peaks at approximately ~ 455 °C and ~ 546 °C, along with a significantly lower weight loss (~ 15 %) and a higher residual mass (~ 85 %). This enhanced thermal stability of MXene-coated membrane enables it to withstand heat treatments such as sterilization, thereby increasing its suitability for antibacterial applications.

The TGA-DSC analysis of MX-3Ag/Mem reveals a multistage thermal behavior. The initial endothermic peaks observed at approximately 49 °C and ~ 113 °C are attributed to moisture evaporation and the release of intercalated solvent, respectively. Two prominent exothermic peaks at around 462 °C and 504 °C correspond to the thermal decomposition of the nylon substrate, oxidation of MXene, and the conversion of silver precursor, possibly associated with Ag nanoparticle formation and polymer degradation. The total mass loss of approximately 23 % further confirms the hybrid nature of the membrane, comprising thermally stable MXene and silver components. These results support the successful incorporation of Ag into the MXene-polymer matrix. The TGA-DSC analysis of the MX-4Ag/Mem sample reveals two-step thermal decomposition behaviour. The initial endothermic peaks observed at approximately 52 °C and 120 °C are attributed to moisture evaporation and the release of intercalated solvent respectively. A major exothermic peak at 466 °C corresponds to the thermal degradation of the polymer membrane, oxidation of MXene and possible crystallisation of silver species. The final residual mass of approximately 7 % indicates the presence of thermally stable MXene and Ag components. Overall, the MX-

4Ag/Mem sample exhibits enhanced thermal stability compared to higher-concentration membranes, which may be attributed to the lower MXene loading and more efficient incorporation of Ag within the matrix, making it suitable for high-performance, thermally stable membrane applications [35].

The FT-IR spectra of Nylon 6,6-membrane, MX02/Mem, MX-3Ag/Mem and MX-4Ag/Mem are presented in the Figure 4.

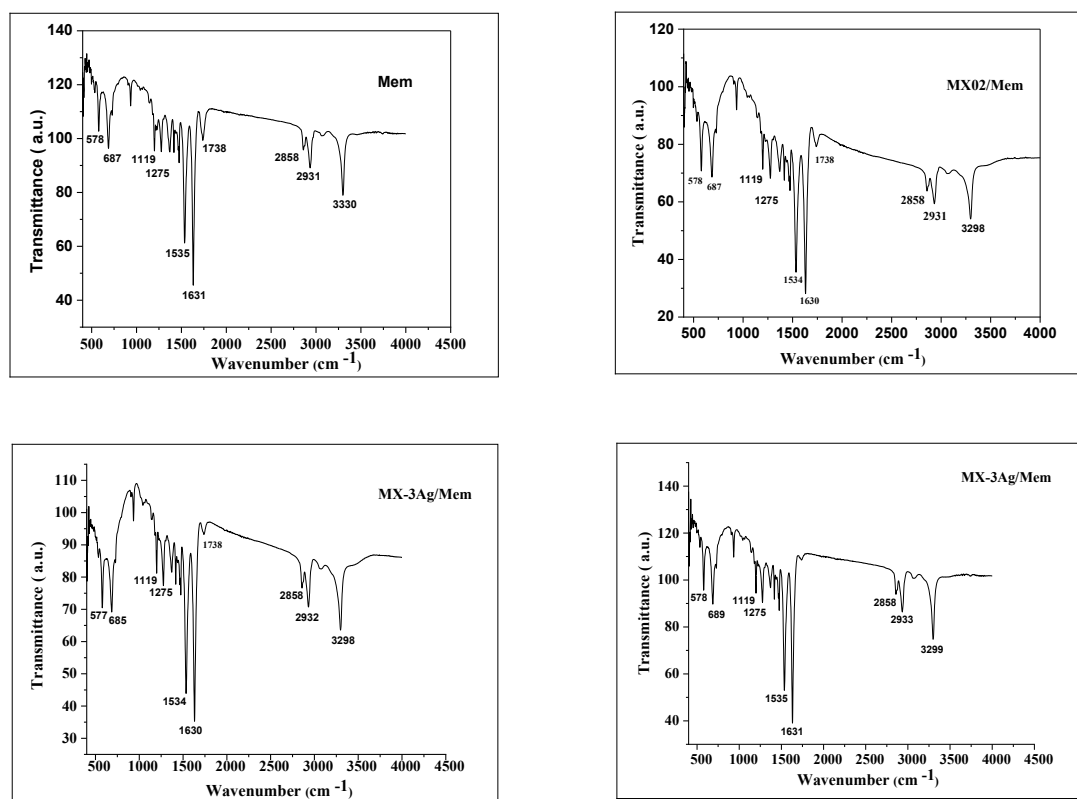
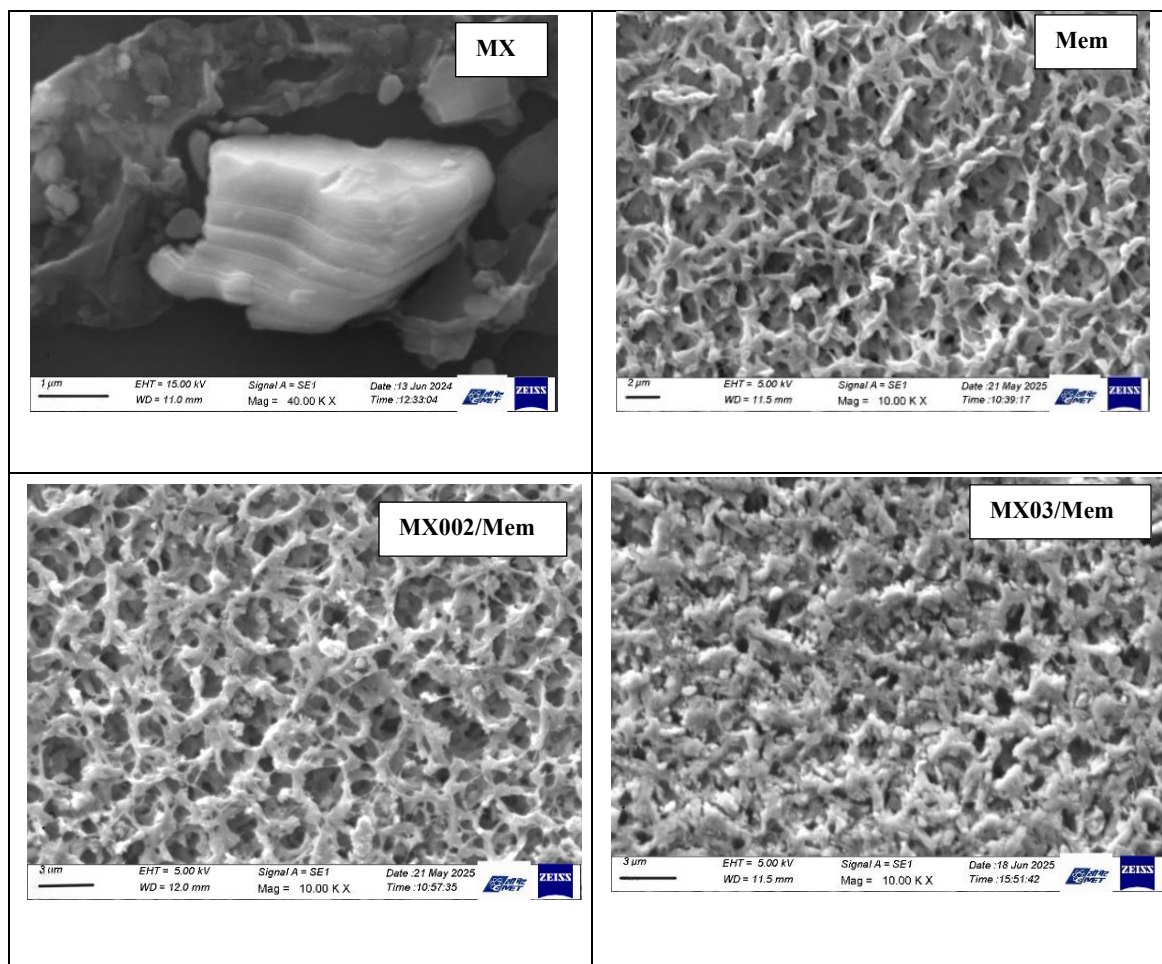


Figure 4. FT-IR spectra of fabricated membranes

In the FT-IR spectrum of Nylon 6,6-membrane, the peak observed at approximately 3330 cm⁻¹ corresponds to N-H stretching vibrations. Peaks at around 2931 cm⁻¹ and 2858 cm⁻¹ are attributed to the asymmetric and symmetric stretching of -CH₂ groups, respectively. The absorption band at ~1738 cm⁻¹ indicates C=O stretching, while the peak at ~1535 cm⁻¹ corresponds to C-N stretching. The band at ~1631 cm⁻¹ is associated with the bending vibration of adsorbed water molecules. Additional peaks observed at ~1275 and 1199 cm⁻¹ are due to C-N and C-C vibrations, whereas the peaks at ~687 and 578 cm⁻¹ correspond to out-of-plane C-H bending vibrations. In the FT-IR spectrum of MX02/Mem, the peak observed at approximately 3298 cm⁻¹ indicates the presence of hydroxyl (-OH) groups and

adsorbed water, which is typical after aqueous etching and washing processes. Peaks at around 2931 cm^{-1} and 2858 cm^{-1} are attributed to C-H stretching vibrations, likely originating from trace ethanol used during intercalation or residual solvent species. The absorption band at $\sim 1738\text{ cm}^{-1}$ corresponds to C=O stretching, suggesting mild surface oxidation or the presence of residual carboxylic groups from environmental exposure or reagents. Peaks at ~ 1630 and $\sim 1534\text{ cm}^{-1}$ are associated with H-O-H bending and Ti-OH deformation vibrations, confirming a hydrated surface and the presence of surface functional terminations [36]. In the fingerprint region, the observed bands correspond to Ti-C and Ti-O vibrations, confirming the layered MXene backbone structure. In the FT-IR spectrum of MX-3Ag/Mem and MX-4Ag/Mem, peaks similar to those observed for MX02/Mem were obtained. Due to the metallic nature of Ag, FT-IR analysis does not typically exhibit distinct Ag-related absorption peaks; however, variations in peak intensity may be observed, indicating interfacial interactions between Ag and the MXene surface.

The scanning electron micrograph images of MXene and fabricated membranes are presented in the Figure 5.



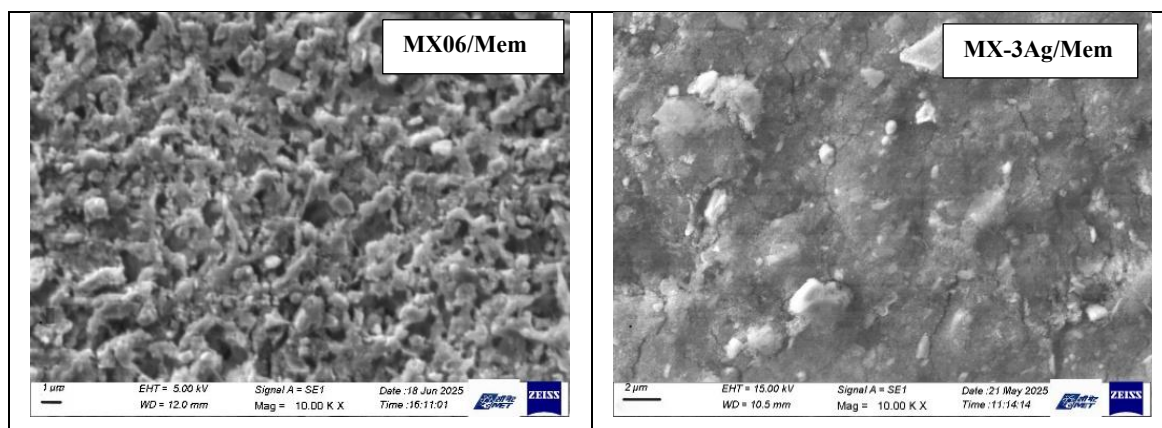


Figure 5. The SE micrographs of MXene, Nylon 6,6-membrane and fabricated membranes

The SE micrograph of MXene shows a layered sheet-like morphology, indicative of successful MAX phase etching [37]. The micrograph reveals highly interconnected, sponge-like porous morphology for the Nylon 6,6-membrane, characterized by irregularly shaped pores that form tortuous pathways rather than straight channels, a structure that enhances permeability while maintaining filtration selectivity. The membrane matrix consists of an entangled nodular and fibrillar polymer framework, forming a three-dimensional skeletal network typical of Nylon 6,6-membrane. The pore sizes fall within the microporous range (sub-micron to a few microns), making the membrane suitable for applications such as microfiltration, support layers in composite membranes, and battery separator or biomedical uses. The pore walls appear relatively rough, which increases the effective surface area and is attributed to crystallization of Nylon 6,6-chains during solvent removal; this surface texture can significantly influence wetting behaviour, protein adsorption etc. The absence of any preferred orientation or layered structure indicates a largely isotropic morphology, consistent with uniform phase separation throughout the membrane thickness.

Upon MXene incorporation, the surface pores of the membrane were progressively filled with MXene flakes, resulting in noticeable changes in surface texture. The membrane containing 0.002 mg mL^{-1} (MX002/Mem) showed lighter coverage of MXene sheets. The MX03/Mem membrane, containing 0.03 mg mL^{-1} MXene, exhibited moderate flake deposition with partial pore coverage. The membrane (MX06/Mem) with the highest MXene concentration (0.06 mg mL^{-1}), displayed dense MXene aggregation, nearly complete pore filling, and a rough, layered surface morphology. The Ag-containing MX-3Ag/Mem sample exhibited a textured surface with clearly visible Ag nanoparticles embedded within the

MXene matrix, confirming successful co-deposition [38]. Overall, these observations indicate that increasing MXene concentration leads to enhanced pore filling and surface roughness, while Ag incorporation introduces additional nanoscale features.

4.0 Antibacterial activity study

The antibacterial activity of the fabricated membranes (Mem, MX02/Mem, MX06/Mem, and MX-2Ag/Mem) was evaluated against *Escherichia coli*, *Pseudomonas*, *Staphylococcus*, and *Enterococcus faecalis* using the agar disc diffusion method. Among all the tested membranes, only the silver-coated MXene membrane (MX-2Ag/Mem) exhibited clear antibacterial activity, producing measurable zones of inhibition against all four bacterial strains. The inhibition zones were 6 mm for *E. coli* and *Pseudomonas*, and 5 mm for *Staphylococcus* and *Enterococcus faecalis*, demonstrating broad-spectrum antibacterial effectiveness. The slightly larger inhibition zones observed for the Gram-negative bacteria (*E. coli* and *Pseudomonas*) compared to the Gram-positive strains suggest enhanced susceptibility, which may be attributed to differences in bacterial cell wall structure. The antibacterial performance of MX-2Ag/Mem is primarily attributed to the presence of silver nanoparticles, which are known to inhibit bacterial growth through multiple mechanisms, including disruption of the cell membrane, generation of reactive oxygen species, and interference with essential cellular processes. In contrast, the pristine membrane (Mem) and the membranes containing lower MXene powder concentrations (MX02/Mem and MX06/Mem) showed no detectable inhibition zones, confirming that they possess negligible intrinsic antibacterial activity under the tested conditions. These findings demonstrate that silver incorporation is essential for imparting effective antibacterial properties to the membrane, making MX-2Ag/Mem a promising candidate for applications requiring both filtration and antimicrobial performance [39].

4. Conclusions

MXene- and MXene–silver-coated nylon 6,6 membranes were successfully fabricated using the vacuum filtration method. The X-ray diffraction analysis confirmed the successful synthesis of few-layered MXene through the characteristic shift of the (002) diffraction peak, indicating increased interlayer spacing after etching. Scanning electron micrographs revealed a uniform, wrinkled, and layered morphology, demonstrating effective deposition of the MXene coating and strong adhesion to the nylon 6,6 membrane surface. FT-IR further verified successful surface functionalization by confirming the presence of characteristic –

OH, –F, and –O surface terminations. Antibacterial studies showed that only the membrane modified with 2 wt% Ag-decorated MXene (MX-2Ag/Mem) at a coating concentration of 0.06 mg/mL exhibited measurable inhibition against *Escherichia coli*, *Pseudomonas*, *Staphylococcus*, and *Enterococcus faecalis*, while membranes without silver modification showed negligible antibacterial activity. The enhanced antimicrobial performance is attributed to the synergistic interaction between MXene's two-dimensional layered structure and reactive surface terminations with the well-established bactericidal properties of silver nanoparticles, which collectively promote membrane disruption, oxidative stress, and inhibition of essential bacterial metabolic processes. Overall, the results demonstrate that silver functionalization significantly improves the antibacterial efficacy of MXene-coated nylon 6,6 membranes without compromising their structural integrity. These findings highlight the potential of MXene–silver-coated membranes as multifunctional materials for antimicrobial filtration, water treatment, protective textiles, and biomedical applications. Future work should focus on optimizing the silver loading, evaluating long-term stability and silver ion release, and investigating filtration performance, cytocompatibility, and durability under practical operating conditions to facilitate their translation into real-world applications.

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Conflict of Interest

There is no conflict of interest among the authors.

Author's Contribution Statement

- Conceptualization, Project administration, Original Draft, Supervision
- Methodology, Formal analysis, Data collection
- Methodology, Formal analysis, Data collection

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