



# Photoresponse, thermal and electrical behaviors of MXene-based polysulfone nanocomposite

Kadir Demirelli<sup>1</sup> · Esra Barım<sup>2</sup> · Aytekin Çelik<sup>3</sup> · Mustafa Yegin<sup>3</sup> · Yunus Aksoy<sup>3</sup> · Özge Hanay<sup>3</sup> · Halil Hasar<sup>3</sup>

Received: 27 September 2023 / Revised: 19 November 2023 / Accepted: 11 December 2023 /  
Published online: 31 January 2024  
© The Author(s) 2024

## Abstract

The  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanosheet was prepared by 40% (v/v) hydrofluoric acid etching at 20 °C for 48 h and delamination of bulk MAX  $\text{Ti}_3\text{AlC}_2$  precursor material. A 2D nanomaterial MXene  $\text{Ti}_3\text{C}_2\text{T}_x$  as a nanofiller was introduced to polysulfone (PSulfone) matrix. MXene and PSulfone/MXene nanocomposite systems were characterized by X-ray diffraction, scanning electron microscopy, transmission electron microscope, Fourier-transform infrared and thermogravimetric analysis instruments. Dielectric and electrical characterization of PSulfone/MXene nanocomposite was carried out. The electrical resistance of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene from measurement current (I)–voltage (V) was measured as 116  $\Omega$ . Pure PSulfone matrix exhibits typical insulator behavior, and MXene exhibits a good conductor behavior. But, when MXene was added to the pure PSulfone matrix, the resistance of the MXene/PSulfone nanocomposite increased moderately compared to that of pure MXene. In spite of the excess of surface functional groups, MXene showed surprisingly good electron transport across the surface, while in the case of PSulfone/MXene nanocomposite, the insulating behavior of PSulfone significantly reduced the electron transport of MXene. The semiconductor behavior of PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanocomposite indicates that MXene provides efficient charge carrier transfer in the nanocomposite system. By comparing the TGA results between the PSulfone and different weight ratios of PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanocomposites, it was determined that MXene nanosheets had a significant effect in slightly accelerating the thermal degradation of PSulfone. Optical conductivity was investigated by preparing a film of PSulfone/MXene nanocomposite on an interdigital contact. It was observed that the optical current values changed depending on the increasing illumination intensity. Considering current–voltage measurements, the photocurrent generation potential of PSulfone/MXene nanocomposite shows that it can be used in photodevice production.

**Keywords** MXene · Polysulfon · Nanocomposite · Dielectric properties · Conductivity · Photoresponse

## 1 Introduction

PSulfones, which contain aryl and sulfonyl groups in their structures, constitute an outstanding class of thermoplastic polymers [1]. They show great resistance with high tension and bending strength under mechanical load. The growing interest in polysulfones is a result of their mechanical strength as well as their high softening points due to their thermal stability. They also have chemical stability as they are able to withstand acids and bases with pH values of 2–13. They can be used in diverse fields including the automotive sector, aviation, electronics and healthcare services due to properties that allow them to achieve optimal performance [2–7]. Polysulfones are commonly used in electronic equipment, such as in the manufacturing of medical devices, coffee machines, microwave ovens and television parts [8]. In a study conducted by adding a chromophore group to polysulfone, it was stated that polysulfones are candidate materials for use in telecommunications [9]. Researchers continue to carry out further investigations to improve the dielectric properties of polysulfones [10]. In studies in which new structures containing polysulfones were manufactured, it was reported that polysulfones can be used as optical sensors and contact lens material [11–13]. Additionally, they are frequently used in membrane technology, and studies in that field are still ongoing [14–16]. PSulfones, like other polymers, can be made into composites. In this direction, one of the 2D materials used as an additive recently is MXene. MXene is a nanosized, honeycomb-shaped, 2D material first reported in 2011. It has a MAX phase; this phase is a three-layered compound with the general formula of  $M_{n+1}AX_n$  (A: one group—A element; M: one early transition metal; X: carbon or nitrogen;  $n$ : 1–4). MXene, whose general formula is  $M_{n+1}X_nT_x$  (T: surface terminals such as  $-O-$ ,  $-OH$ ,  $-F$  or  $-Cl$ ), is obtained by etching the aforementioned phase with acids such as HF, HCl,  $H_2O_2$  or their mixtures [17–20]. Since its discovery, MXene has become popular in material science with its versatile properties and it has found applications in many fields. For example, its use has been reported in diverse industrial applications thanks to its optical properties and high mechanical strength [21, 22], and it has been used in electronic devices [23] and electrochemical biosensors [24] for its high electrical conductivity. When MXenes are composited with polymer matrices, MXenes with excellent mechanical properties, hydrophilic surfaces and metallic conductivities can further improve the mechanical and thermal properties of polymers. MXene is undergoing continuous improvement for applications in biomedical (electrical stimulation of wound healing, 3D bioprinting), supercapacitor (electrodes, electrolytes, sensors), telecommunications and optical fields [25, 26]. On the other hand, many polymer composites with mechanical, thermal, electrochemical, electrical and abrasion resistance have been prepared by adding MXenes to many polymer matrices such as polyvinylalcohol (PVA) [27], polypyrrole [28], polyethylene (PE) [29] or polydimethylsiloxane (PDMS) [30]. Composites prepared by adding MXene to PSulfone matrices have been used especially in membrane construction. MXene was introduced as nanofillers into quaternized polysulfone/polyquaternium-10 (QPSU/PQ-10) anion exchange membranes (AEMs)

with semi-interpenetrating polymer network [31]. PSulfone is widely applied in the fabrication of nanofiltration membranes. MXene, as a promising nanomaterial in the hydrophilicity improvement of polymeric membranes, has been incorporated into the PSulfone nanofiltration membranes [32]. MXene ( $\text{Ti}_3\text{C}_2\text{T}_x$ ) was incorporated into PSulfone membrane to fabricate a new kind of nanocomposite membrane, which has an improved hydrophilicity and antifouling performance [33].

This study focuses on examining the PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanocomposite, which is prepared by combining the exceptional properties of MXene with the PSulfone matrices, whether it can be used as a good photosensor, whether it can be used as a new charge storage material, and how the optical current values will change depending on the increasing illumination intensity. In a previous study, it was revealed that MXene oxidized rapidly after 390 °C. However, one of the questions was how MXene would behave in the polymer matrices. Therefore, understanding whether MXene oxidizes in the composite when MXene is added to PSulfone and how it affects the thermal degradation of PSulfone has been another curiosity. The pure MXene and MXene/polymer nanocomposites have been used in sensor applications to detect toxic compounds in water and food materials. However, according to our research, since MXene and PSulfone nanocomposite application has still not found its place in the literature studies, the fact that such an MXene/PSulfone nanocomposite has photoresponse behavior emphasizes the importance of the study.

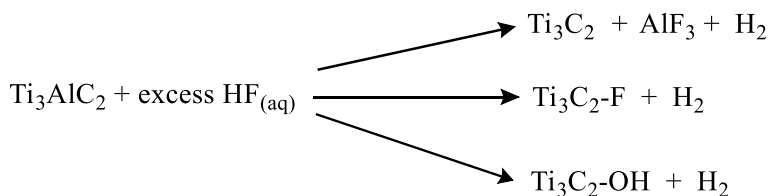
## Materials and methods

### Materials

$\text{Ti}_3\text{AlC}_2$  (MAX phases,  $\leq 100$  nm), hydrofluoric acid (HF for 48% solution,  $d = 1.15$  g/mL, ACS reagent), N,N-dimethyl formamide (DMF,  $\geq 99.8\%$ ) and PSulfone were obtained from Sigma-Aldrich Inc.

### Characterization

FT-IR spectra of MXene flakes and residue of MXene heated up to 600 °C were recorded on PerkinElmer Spectrum Two Instrument equipped with ATR. X-ray diffraction (XRD) patterns were achieved by PANalytical Empyrean XRD at 5 kV voltage and 40 mA current with Cu-K $\alpha$  radiation ( $\lambda = 1.5406$  Å) with a  $2\theta$  range of 10–90° and used to study the crystal structures of  $\text{Ti}_3\text{AlC}_2$  MAX phase and  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene phase. The SEM images and energy-dispersive X-ray spectroscopy (EDX) analysis were carried out using field-emission electron microscope gun and with a 4-Segment Backscatter Electron Detector (BSD). Transmission electron microscope (TEM) analysis was achieved by lanthanum hexaboride ( $\text{LaB}_6$ ) electron Hitachi HT-7700 brand device with gun, operating under accelerating voltage in the range of 40–120 kV feature. FYtronix 9000 Solar Simulator I–V characterization system was used for measurement of MXene-loaded PSulfone nanocomposites. The TGA



**Scheme 1** Formation of MXene products

measurements of pure PSulfone and MXene-loaded PSulfone nanocomposites were heated from room temperature to 600 °C using samples around 5 mg at a heating rate of 10 °C/min under air, 10 mL argon gas flow using Shimadzu TGA-50 instrument.

### Synthesis of MXene

Naguib et al. synthesized the first  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene, by immersing  $\text{Ti}_3\text{AlC}_2$  [34] powders in 50% concentrated hydrofluoric acid (HF) at room temperature for 2 h. According to adapted method from literature [35]:  $\text{Ti}_3\text{AlC}_2$  powder (1 g) was introduced in 28 mL of a 40% (v/v) HF solution. The mixture in a plastic vessel was stirred for 5 min, and then kept at temperature of 20 °C for 48 h. The suspension solution was washed using deionized water several times until the pH of the suspension solution is neutral. Afterward, it was centrifuged to separate MXene powder after every washing with distilled water. Then, the washed powders were filtered under vacuum at 65 °C. Dried MXene was poured into 20 mL DMF and ultrasonicated for 15 min to form a homogeneously dispersed suspension solution. Then, it was dried under a vacuum oven at temperature of 65 °C for 24 h and stored in a dark-airless environment. When  $\text{Ti}_3\text{AlC}_2$  is immersed in HF solution, etching reactions may produce products bearing terminal functional groups as follows [36]. Among the products,  $\text{Ti}_3\text{C}_2$ , which is basic and has high surface activity, is first produced, followed by –OH and F-terminated MXene structures.  $\text{T}_x$  in the formula  $\text{M}_{n+1}\text{X}_n\text{T}_x$  contains –OH, –F and –O– surface functional groups. The MXene product synthesis scheme can be summarized as in Scheme 1.

### Preparation of PSulfone/MXene nanocomposites

$\text{Ti}_3\text{C}_2\text{T}_x$  powder (40 mg) was immersed in chloroform, and the mixture was sonicated for 1 h. Meanwhile, the corresponding PSulfone (137 mg) was entirely dissolved in chloroform and poured into the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene suspension. The solution collected was stirred by a magnetic stirrer for 10 min. The mixture was precipitated within ethylalcohol at room temperature, and it was filtered. The polymer nanocomposite was dried under air atmosphere, later it was put into a vacuum oven and dried at a temperature of 50 °C for 24 h to remove the residue of chloroform. Afterward, the dried polymer nanocomposite was compressed to form pellet under a pressure of 4 tons. This polymer nanocomposite contains MXene 22.5 wt%. Another polymer nanocomposite was prepared according to the same procedure.

## Results and discussion

### XRD patterns of pure MXene and PSulfone/MXene nanocomposites

The structural characteristics of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene and PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  nanocomposite and MAX precursor were investigated by XRD pattern. The strongest peak of  $\text{Ti}_3\text{AlC}_2$  is at  $2\theta = 38.96^\circ$  (107 plane). The strongest signals of MAX precursor at  $38.96^\circ$  disappear that Al layers are almost etched away after etching with 40% (v/v) HF for 48 h. The intense peak at  $38.6^\circ$  is much lower, and this change indicates that Al layers in  $\text{Ti}_3\text{AlC}_2$  are easily removed in an effective fashion. The X-ray diffraction patterns for  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene and PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  nanocomposites (MXene 2.5, 7.5 and 15.0 wt%) mixed to PSulfone matrix are shown in Fig. 1a–d. Figure 1a indicates XRD spectrum of PSulfone containing MXene 2.5 wt% very weakly showing  $2\theta = 34$  to  $38.6$  degree peaks characteristic for MXene. The peaks, which are indicative of MXene indicated in Fig. 1a, are at  $18.3$  (004 plane),  $23.2$  (006 plane) and  $27.5$  (008 plane). As indicated in Fig. 1b, c and d, the PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  15 wt%, 7.5 wt% and 2.5 wt% nanocomposites showed a slightly weak characteristic (002) peak that shifts from  $8.13^\circ$  ( $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes) to  $7.64^\circ$ , which corresponds to the expanding interlayer spacing due to the accumulation of PSulfone molecules into the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene galleries [37]. In Fig. 1b, c and d, the apparent diffraction degrees of MXene in the polymer matrices become more pronounced as the amount of MXene increases. And the diffraction degrees such as  $2\theta = 8.55$ ,  $27.88$  and  $40.48^\circ$  are particularly evident for MXene in the PSulfone matrix. The broad peak centered at  $2\theta = 17.6^\circ$  is characteristic for PSulfone structure and indicated an almost amorphous structure. Regarding the PSulfone– $\text{Ti}_3\text{C}_2\text{T}_x$  MXene pattern, the XRD pattern shows that the presence of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene does not significantly

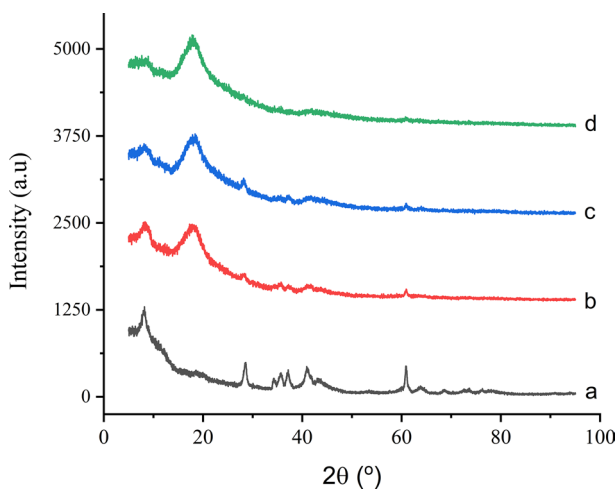


**Fig. 1** X-ray diffraction (XRD) patterns of **a** pure MXene produced by etching 20.0 (v/v)% HF solution at  $40^\circ\text{C}$  for 48 h, **b** PSulfone/MXene 15.0 wt%, **c** PSulfone/MXene 7.5 wt% and **d** PSulfone/MXene 2.5 wt%

change the structure of PSulfone as it keeps the specific diffraction peak constant at about  $2\theta = 17.6^\circ$ . Moreover, incorporation of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene into the PSulfone matrix resulted in a slight narrow peak in the flat region resulting from the amorphous structure of PSulfone, resulting in a slight increase in the structural order of the polymer. Furthermore, as the addition of MXene to the PSulfone matrices increased, the characteristic diffraction peak intensities slightly increased and its arrangement in PSulfone– $\text{Ti}_3\text{C}_2\text{T}_x$  MXene compared to neat PSulfone. The absence of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene characteristic diffraction pattern at  $2\theta$  of about  $27.88^\circ$  between  $34$  and  $48^\circ$  in the sample suggested a good dispersion of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene within the polymer matrices.

The XRD spectrum of residue of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene heated to  $600^\circ\text{C}$  under air atmosphere showed quite different diffraction degree from that of pure MXene, as compared in Fig. 2a and b. Figure 2a is the XRD pattern of pure  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene. The XRD pattern of  $\text{Ti}_3\text{C}_2$  MXene indicates at the important diffraction degrees at  $8.0$ ,  $27.88^\circ$ , between  $34^\circ$  and  $38^\circ$ ,  $40.48^\circ$ ,  $60.8^\circ$ . As shown in Fig. 2b, the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene structure changed significantly to the rutile and anatase  $\text{TiO}_2$  structure. The most pronounced diffraction grades for the anatase  $\text{TiO}_2$  structure are:  $27.39^\circ$ ,  $38.57^\circ$ ,  $48.06^\circ$ ,  $53.89^\circ$  and  $62.69^\circ$ . In addition, as shown in Fig. 2c, diffraction degrees such as  $27.39^\circ$  and  $54.27^\circ$  characterize the rutile  $\text{TiO}_2$  structure. When PSulfone/MXene 10 wt% is heated up to  $600^\circ\text{C}$  under an air atmosphere,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene turns into  $\text{TiO}_2$  structure, especially from very small signals at  $25.37$  (anatase),  $48.1$  (anatase) and  $61^\circ$  (for anatase) degrees. On the other hand, it is understood from the significant disappearance of the wide band at  $2\theta = 17.6^\circ$  that the PSulfone in the nanocomposite also degrades when heated to the same temperature. It consists of a multiple decomposition reaction of the thermal decomposition process when the PSulfone polymer is heated in an inert gas atmosphere. Some of them

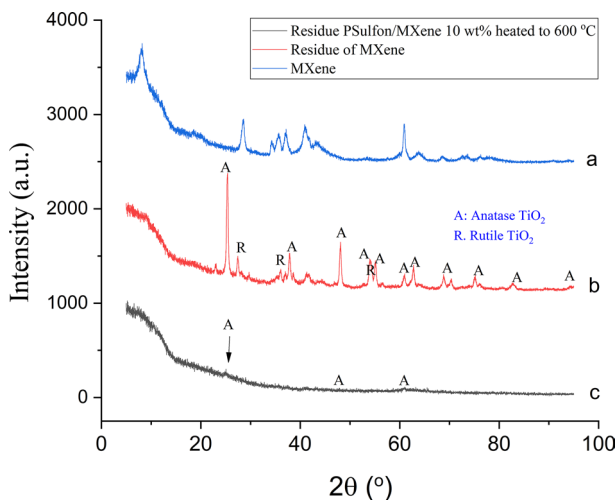


**Fig. 2** X-ray diffraction patterns of **a** MXene, **b** residue of MXene heated to  $600^\circ\text{C}$  under air atmosphere and **c** residue of PSulfone/MXene 10 wt% heated to  $600^\circ\text{C}$  under air atmosphere

are decomposition reactions such as process of breakdown of ester bonds under the action of  $\text{SO}_2$ , breakdown of ester aryl- $\text{SO}_2$  bonds, radical reactions of proton transfer from aryl fragments and formation of a densely cross-linked condensed aromatic structure of char [38, 39].

### SEM and TEM analysis of MXene

The 50.0 kX magnification SEM images of  $\text{Ti}_3\text{C}_2\text{T}_x$  produced by exfoliating  $\text{Ti}_3\text{AlC}_2$  etched by HF for 48 h are showed in Fig. 3a. The surface of  $\text{Ti}_3\text{C}_2\text{T}_x$  is rough, and the layered edge is attached by small balls with the diameter of around 30 nm. Nanosized  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene particles smaller than 50 nm have been confirmed. The diameter of  $\text{Ti}_3\text{AlC}_2$  MAX used as precursor was bigger than 50 nm. Whereas, that of MXene was much small than 30 nm. This difference is suggested to be related to the removal of Al layers from the MAX phase and the thorough sonication of the produced  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene.

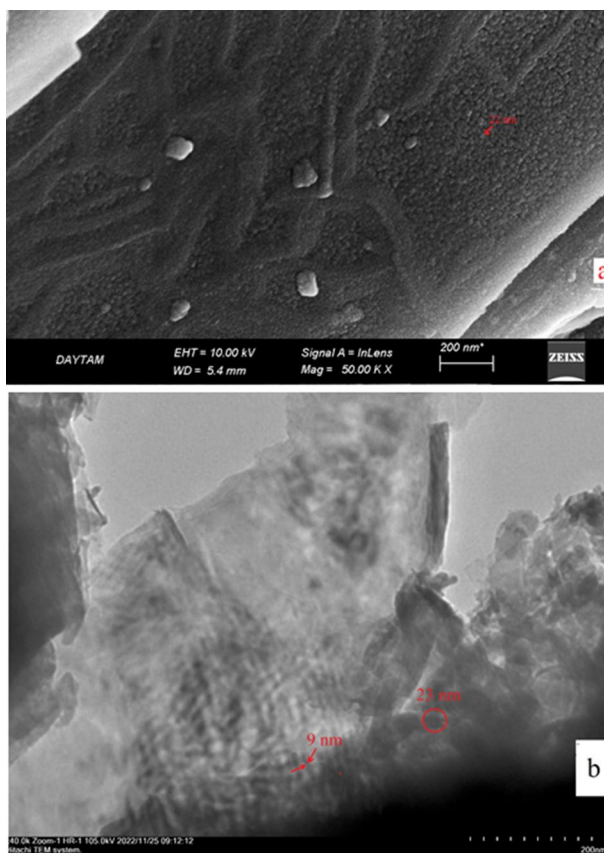
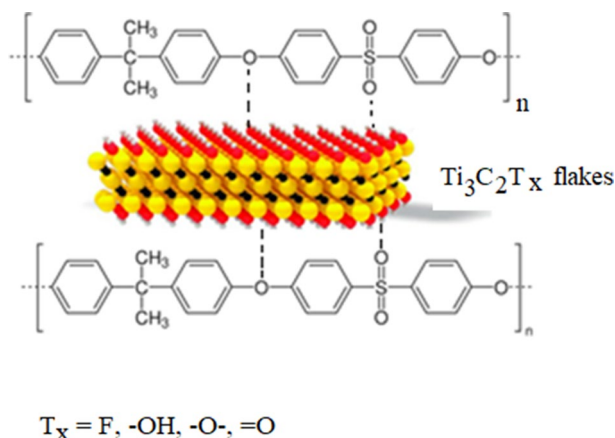


**Fig. 3** Images of **a** SEM and **b** TEM for  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene



**Scheme 2** Physical attractions between PSulfone and MXene nanosheets

Figure 3b shows TEM images of  $Ti_3C_2T_x$  MXene' size distribution. As shown in Fig. 3b, TEM analysis of the exfoliated layers indicates that they are quite thin and transparent to electrons. This property, as depicted by the TEM image in Fig. 3b, indicates that the prepared  $Ti_3C_2T_x$  is composed of not a single but several monolayers, bound by weak van der Waals forces. Aggregates of 100 nm in size were found in the TEM images of  $Ti_3AlC_2$  MAX, and the size distribution was determined as that of the primary particles. The nanoparticles were thereby revealed to have an average diameter of 23 nm. TEM analysis of the exfoliated MXene layers indicates that they are quite thin and transparent to electrons. As shown in Fig. 3b, MXene layers are not a single layer, but it consists of several layers. Each MXene layer thickness was seen in the range of the 4–9 nm and quite thin. On the other hand, it is understood that the average diameter of MXene particles is smaller than 50 nm. It can be said that these data are consistent with each other as understood from the SEM analyzes of the surface particles. What has been described so far based on FT-IR, XRD and SEM–EDX, XPS (X-ray photoelectron spectroscopy) and TEM results confirmed that  $Ti_3C_2T_x$  nanosheets with a typical MXenes structure are successfully obtained by HF-induced delamination.

### SEM and EDX analysis of PSulfone/MXene nanocomposites

Since the surface of MXenes carries polar functional groups, it reveals the hydrophilic property of MXene. This property is an indication of why MXene is compatible with polysulfone and forms a good homogeneous composite. Scheme 2 is showing the physical interaction of the surface of MXene with PSulfone.

SEM image of PSulfone/MXene containing 15.0 wt% nanocomposite is indicated in Fig. 4a. The SEM micrograph of the PSulfone/MXene 15 wt% surface shows a comparatively smooth surface. The fractured surfaces of the nanocomposite show a uniform distribution of  $Ti_3C_2T_x$  MXene particles as white dots in the PSulfone matrix. In addition, after adding MXene to the PSulfone matrix, MXene appeared as

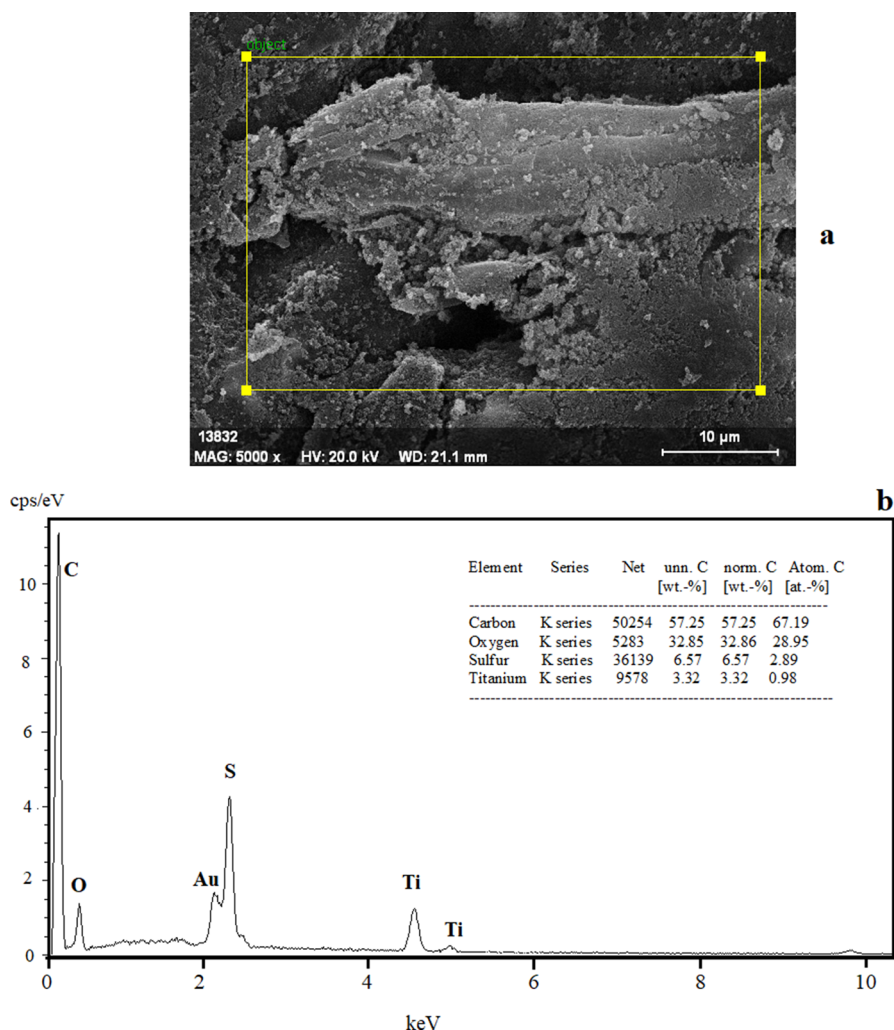


**Fig. 4** **a** SEM image **b** EDX spectrum of PSulfone/MXene 15 wt%

smooth-surfaced spheres in a harmonious existence within the polymeric network. On the other hand, it indicates that MXene from the SEM image shows homogeneous distribution without forming aggregates. While MXene is understood to be in crystalline or granular structure, the particles have been shown to be in a network structure with an average diameter of 30 nm. A lighter color is noticed around the MXene as a sign of the interfacial bond surrounding the PSulfone matrices. In this context, the presence of MXenes in the polymer matrices shows the hope that it is advantageous and will contribute significantly to the physical performance of the prepared composites. The EDX spectrum of MXene/PSulfone composite is shown in Fig. 4b. The EDX spectrum given in Fig. 4b shows the presence of Ti, S, C and O

as the only elementary components of the nanocomposite. The presence of titanium, carbon, fluorine and oxygen in PSulfone/MXene nanocomposite is the proof for presence of MXene surface or within nanocomposite (Fig. 4b), which was absent in neat PSulfone. In addition, this uniform dispersion indicates that the compatibility issue of hydrophilic MXene with amphiphilic PSulfone is greatly improved by organic functionalization.

### FT-IR analysis

As shown in Fig. 5, FT-IR spectra of neat PSulfone and PSulfone/MXene 22.5 wt% were compared with each other. The aromatic ring stretching vibrations are observed at 1580 and 1503  $\text{cm}^{-1}$  for the PSulfone/MXene nanocomposites which are comparative with the vibration that are seen for the PSulfone. The vibrations due to the sulfone moiety are also observed at 1321 and 1147  $\text{cm}^{-1}$  for the asymmetric and symmetric stretching vibrations, respectively. The C–O stretching between two aromatic rings was at 1234 and 1012  $\text{cm}^{-1}$  [asymmetric (aryl)C–O–C(aryl) stretching]. The bands at about 1080 and 1013  $\text{cm}^{-1}$  showed the vibration of C–C bonds on PSulfone structure. It showed that there were no significant differences in the FT-IR spectra of pure PSulfone- and MXene-based polymer nanocomposite. Since the presence of functional groups such as F, OH and O on the surfaces of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene makes MXene more polar, it is understood that the O=S=O groups in the structure of the

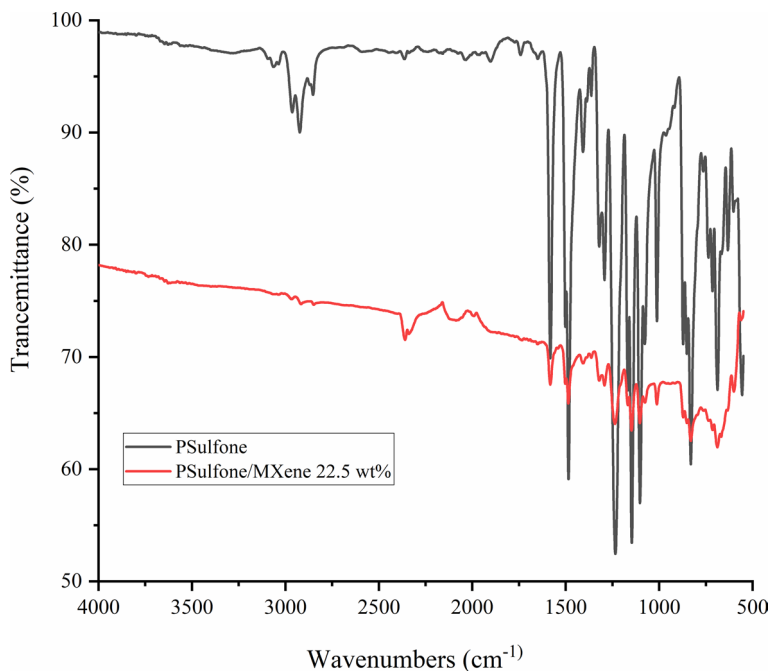


**Fig. 5** FT-IR spectra of **a** neat PSulfone and **b** PSulfone/MXene

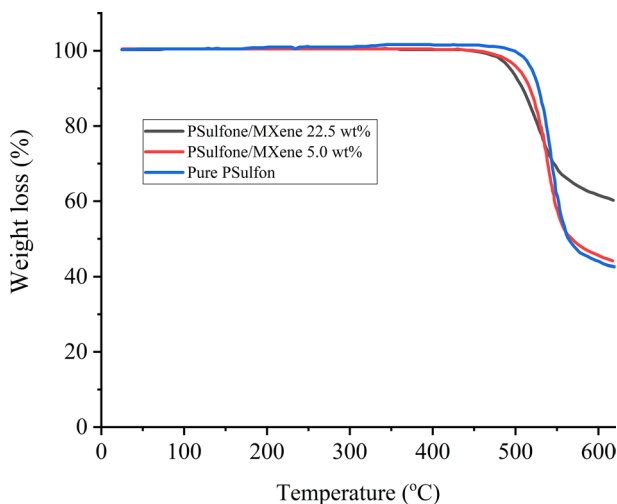


**Fig. 6** TGA curves recorded under argon gas (10 mL/min) at a heating rate of 10 °C/min of the polymer matrix (blue curve), PSulfone/MXene 5 wt% nanocomposite (red curve) and PSulfone/MXene 22.5 wt% nanocomposite (black curve)

**Table 1** TGA data of PSulfone and its nanocomposites

| Samples                                             | IDT <sup>a</sup> (°C) | Temperatures (°C) at % weight loss |     |     |     |     | % Residue at 620 °C |
|-----------------------------------------------------|-----------------------|------------------------------------|-----|-----|-----|-----|---------------------|
|                                                     |                       | 10                                 | 20  | 30  | 40  | 50  |                     |
| PSulfone                                            | 487                   | 528                                | 537 | 545 | 552 | 564 | 42                  |
| Ti <sub>3</sub> C <sub>2</sub> T <sub>x</sub> MXene | 477                   | 518                                | 530 | 539 | 548 | 568 | 43                  |
| PSulfone/MXene 22.5 wt%                             | 476                   | 509                                | 528 | 548 | 617 | –   | 59                  |

*a*: Initial decomposition temperature

PSulfone form a well-miscible composite that is compatible with each other and creates a physical interaction. However, the physical interactions between PSulfone and MXene show that they affect the band stretching energies.

## TGA measurements

TGA curves measured under argon gas flow, of the nanocomposite PSulfone/MXene 22.5 and 5 wt% and the polymer matrices (PSulfone), are indicated in Fig. 6, and the results are summarized in Table 1. The initial thermal decomposition or differences of stability of these samples heated under argon atmosphere possess a little differ from each other. Polysulfone is more thermally stable than PSulfone composites loaded MXene 5 and 22.5 wt%, and its thermal degradation starts at 487 °C, compared to 477 and 476 °C for PSulfone with MXene, respectively. And decomposition of the three samples occurs in one stage. While PSulfone showed 10% weight

loss at 528 °C, PSulfone/MXene 22.5 wt% showed at 510 °C. This behavior suggests that the polymer matrix facilitates chain breaks, as a result of homogeneous distribution of  $\text{Ti}_3\text{C}_2\text{T}_x$  nanoparticles between PSulfone chains. In other words, this event indicates that layered MXene nanolayers accelerate thermal degradation of PSulfone and somewhat reduce thermal stability. However, it has been noted in literature data that MXene retards its thermal degradation of polystyrene [40]. In general, fillings added to the polymer matrix are known to decrease or increase thermal stability. In a previous study, it was stated that pure MXene increased in weight when heated in air atmosphere or a low inert gas atmosphere, and it was converted into  $\text{TiO}_2$  to a large extent as a result of oxidation. However, as shown in Fig. 6 at our study, the absence of weight gain in the TG curves of the two nanocomposites probably indicates that the PSulfone matrices significantly indicate the oxidation of MXene. The residual amounts of the three samples were also different from each other. The polymer nanocomposite containing MXene 22.5 wt% showed 59% residue, while pure PSulfone showed 42% residue. From these results, it is understood that MXene is significantly preserved in the polymer nanocomposite.

## Dielectric measurements

Dielectric properties can be expressed by relative complex permittivity ( $\epsilon^* = \epsilon' - j\epsilon''$ ). The real part of the complex permittivity ( $\epsilon'$ ) is proportional to the amount of electric charge stored at the surface, or a measure of the polarizability of a material when exposed to an applied electric field. That is related to the ability to store energy. The imaginary part of the relative complex permittivity ( $\epsilon''$ ) describes the energy loss while in the applied electrical field. Figure 7 shows the  $\epsilon''$  and dielectric loss of only  $\text{Ti}_3\text{C}_2\text{T}_x$  nanosheets and the polysulfone composite loaded 22.50 wt%  $\text{Ti}_3\text{C}_2\text{T}_x$  powders. Also, these features are shown in comparison with those

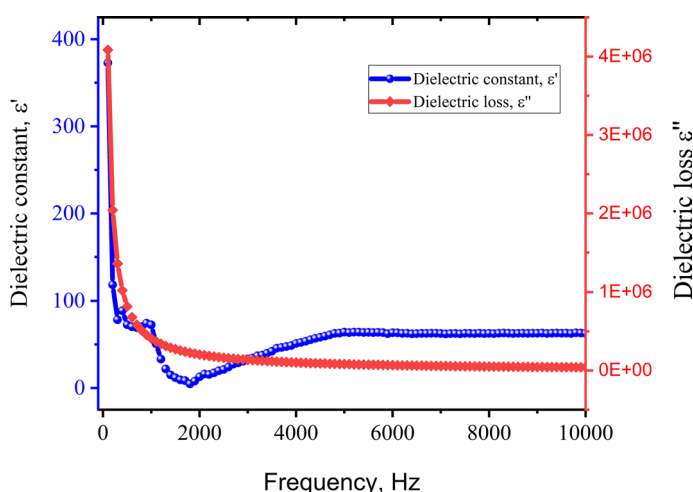


**Fig. 7** Change of dielectric constant and dielectric loss with frequency of PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene

of the MAX as shown in Fig. 7. The  $\epsilon'$  and  $\epsilon''$  of PSulfone/MXene nanocomposite were 72.4 and 408,829 at 1 kHz and room temperature, respectively. Thus, polarization and interfacial polarization occur as a result of the number of interfaces between  $\text{Ti}_3\text{C}_2\text{T}_x$  nanolayers and PSulfone and more electron relaxation under the applied electric field. From this point of view, it is possible for  $\text{Ti}_3\text{C}_2\text{T}_x$  nanolayer filled composites to have higher  $\epsilon'$  values. Noticeably, the dielectric loss decreases as the frequency increases, especially at low frequencies (see from Fig. 7). In low-frequency range, the charge polarization time is insufficient, resulting in a gradually decrease in dielectric loss. The dielectric loss of the PSulfone/MXene 22.5 wt% is in the range of 408,829.6 at 1 kHz, 204,526.7 at 2 kHz at room temperature. However, it is 41,032.9 at 10 kHz and room temperature. This shows that the dielectric loss decreased around 10 times as the frequency changed from 1 to 10 kHz. The MXene in the nanocomposite produced from PSulfone with MXene terminated with various polar functional groups could restrict the movement of macromolecular chains and thus resulting stable dielectric loss in increasing frequency after 4 kHz. Whereas, the dielectric constant of PSulfone has been found as 2.1 at 1 kHz, while the dielectric loss is only 0.007 [41]. When MXene 5 wt% to PSulfone matrix was added, the dielectric constant changed to 3.34. But dielectric loss not changed in comparison that of pure PSulfone. The variation of alternative current (ac) conductivity with frequency of PSulfone/MXene 22.5 wt% nanocomposite is shown in Fig. 8. As shown in Fig. 8, at low frequencies, conductivity did not change with frequency. This change versus direct current conductivity for the sample is coming. Moreover, as MXene increases, the dipolar contribution is reduced as a result of depression in the molecular motions. Consequently, the conductivity of nanocomposite is strongly independent on frequency. At high frequencies, nanocomposite's AC conductivity confirms to the  $\sigma \propto \omega^S$  relation. To determine the AC conductivity mechanism of nanocomposite, the  $s$  value was estimated. In this regard, the conductivity follows a power law relation;  $\sigma = \sigma_{dc} + A\omega^n$ , where  $\sigma_{dc}$  is the DC conductivity,  $\omega$  is the angular

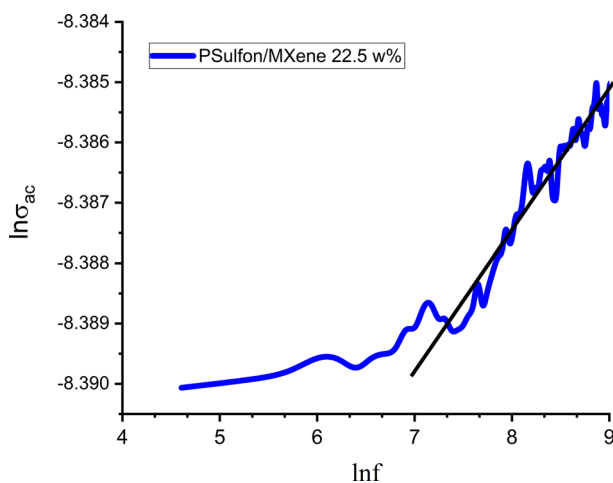


**Fig. 8** Plot of AC conductivity versus frequency for PSulfone/MXene nanocomposite

frequency, ( $A$ ) is a frequency independent parameter and  $n$  is a power. The values of  $n$  are found to be  $n < 1$ , which is governed by electronic hopping processes. So, the  $s$  value was calculated from the slope of the curve in Fig. 8. Since  $s$  value is  $0 < 0.0023 < 1$ , CBH (correlated barrier hopping) shows that it fits the conductivity mechanism [42]. However, the inclusion of MXene increased the space charge density in addition to these intrinsically stimulated by the presence of hard and soft segments in the PSulfone matrix. Meanwhile, the MXene treatment has positively affected the electrical conductivity.

## Electrical measurements

To understand the effect of MXene on the electrical properties of PSulfone, different amounts of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene were added to the PSulfone matrix and the electrical conductivity of PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanocomposite increased considerably compared to PSulfone.

The conductivity was calculated from the following Eq. (1):

$$\sigma = \frac{1}{R} \cdot \frac{d}{s} \quad (1)$$

where  $\sigma$  is the conductivity (expressed in units of  $\text{Scm}^{-1}$ ),  $R$  is the resistance of the nanocomposite (in ohms,  $\Omega$ ),  $d$  is thickness of nanocomposite (in cm) and  $S$  is the surface area of the nanocomposite (given in  $\text{cm}^2$ ). The electrical conductivity of the PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  22.5 wt% composites increased was found to be  $5.87 \times 10^{-4} \text{ S/cm}$ , which was much higher than that of pure PSulfone ( $10^{-12} \text{ S/cm}$ ). PSulfone molecular chains can intercalate to MXene layers and form a conductive network. This means that it allows the conduction of electrons in the nanocomposite and leads to the formation of higher conductive channels. In the literature studies, conductivity measurements were revealed by adding MXene to some commercial polymers. Some of them,  $\text{Ti}_3\text{C}_2\text{T}_x$  into PVDF matrices for constructing a conductive network was incorporated by Rajavel et al. [43]. Rajavel et al. revealed that the conductivity increased from  $2.8 \times 10^{-5}$  to  $0.988 \text{ S/m}$  when increasing the addition of MXene to the PVDF matrices from 4.61 vol% to 22.5%. In addition, MXene was also incorporated into PVA [44] and PS [45] matrices to investigate the enhancement influence of MXene on the conductivity of polymer, and it was confirmed that MXene increased conductivity of polymers. When 19.5 wt% MXene to PVA matrices and 1.90 vol % to PS matrices were added, the conductivity of  $\text{Ti}_3\text{C}_2\text{T}_x/\text{PVDF}$  and  $\text{Ti}_3\text{C}_2\text{T}_x/\text{PS}$  increased to 716 and 1081  $\text{S/m}$ , respectively. Hence, it confirms that when MXenes are added to polymer matrices, polymer composites produced can form a denser conduction network between polymer chains to increase their electrical conductivity and improve the conduction capacity of electrons. MXenes, which make important contributions to the electrical conductivity of polymer matrices, show that they have important advantages by forming a relatively new class of graphene-like 2D layered nanomaterials that are also attracting great attention due to their excellent thermal stability and mechanical properties [46, 47]. The two different graphs of

current–voltage indicated that the current linearly increased with increasing voltage. The resistance of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene indicated in Fig. 9a is  $116\ \Omega$ . The increase in resistance ( $R$ ) of MXene may be due to abundant surface terminations obtained by wet chemical etching process. However, MXene possesses the excellent electrical and electronic performance. As shown in Fig. 9b, the resistance of PSulfone/MXene 22.5 wt% significantly increased to  $R=33,000\ \Omega$ . By doping with 22.5 wt% MXene to PSulfone matrices, the volume resistance of the PSulfone increases significantly, but decreases for higher doping levels. This is consistent with variation in trap parameters. Besides, deep traps easily catch the carriers,

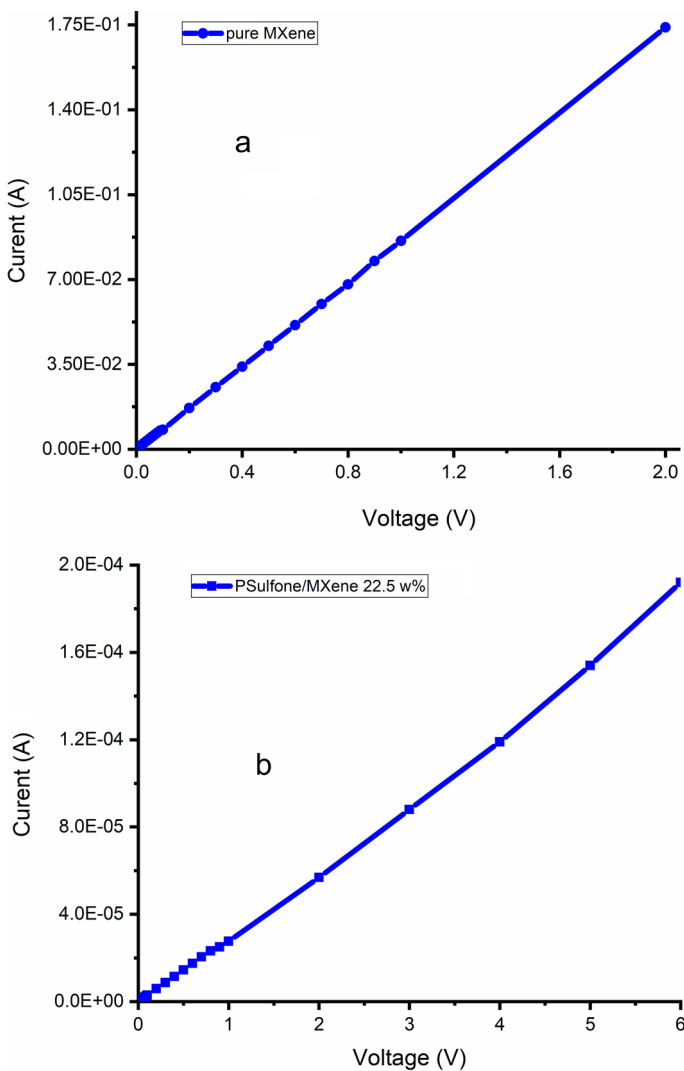


**Fig. 9** I–V characteristics **a**  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene and **b** PSulfone/MXene 22.5 wt%

making it easier for the carriers to sink but difficult to escape, thus reducing the kinetic energy of the carriers and increasing the volume resistance.

### Photoresponse behavior of PSulfone/MXene nanocomposite

Film of PSulfone/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> 22.5 wt% on an interdigit system, as shown in Fig. 10, was prepared. I–V curves depending upon sunlight response of PSulfone/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> 22.5 wt% nanocomposite are drawn and presented in Fig. 11. It is observed a significant increase in the surface photoconductivity of polymer nanocomposite due to illumination with a sun source having a power density of 20, 40, 60, 80 and 100 mW/cm<sup>2</sup>. During the measurement, a fixed distance (2.5 cm) between sensor device (film) and sunlight source was maintained for all the PSulfone/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> 22.5 wt% sensor devices. While it shows linear behavior up to 0.5 V at all illumination intensities, it has a nonlinear behavior in the range of 0.5 to 1 V. It is clear that the I–V curves have two distinctive linear region (R1 and R2) with different slopes (*m*) and also obey to a power law ( $I \sim V^m$ ) [48, 49]. The value of power exponent, *m*, can be easily from the slope of I–V curve for linear region for R1 in 20, 40, 60 and 100 mW/cm<sup>2</sup> conditions. Thus, the *m* values for R1 linear parts were found as  $9.07 \cdot 10^{-4}$ ,  $8.43 \cdot 10^{-4}$ ,  $8.23 \cdot 10^{-4}$ ,  $7.99 \cdot 10^{-4}$  and  $7.76 \cdot 10^{-4}$  under 20 mW/cm<sup>2</sup>, 40 mW/cm<sup>2</sup>, 60 mW/cm<sup>2</sup>, 80 mW/cm<sup>2</sup> and 100 mW/cm<sup>2</sup>, respectively. At 0.5 voltage, the current values at 20 mW/cm<sup>2</sup> and 100 mW/cm<sup>2</sup> illumination intensities were observed as 0.384 and 0.478 mA, respectively, while at 1 voltage, the same illumination intensities changed from 1.04 to 1.41 mA. From these data, it can be stated that the polymer nanocomposite has optical conductivity behavior with increasing voltage. One can easily see that the conductivity at 100 mW/cm<sup>2</sup> under UV illumination is significantly higher than 20 mW/cm<sup>2</sup> for polymer nanocomposite indicating a very good photoresponse behavior. From the current–voltage graph, as shown in Fig. 12, the current increases with increasing illumination intensity, that

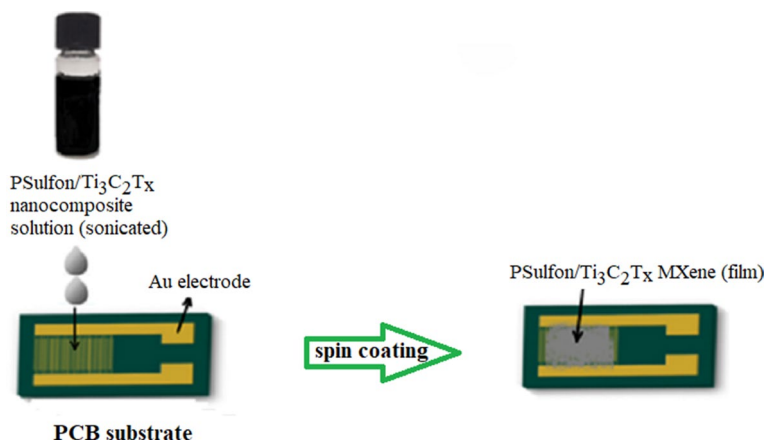


**Fig. 10** Preparation of PSulfone/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> 22.5 wt% film by means of interdigital system on PCB (printed circuit board) substrate

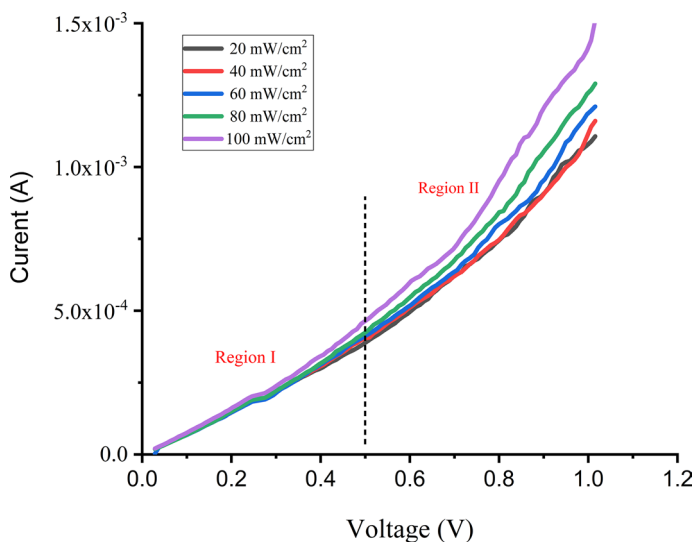


**Fig. 11** The current–voltage (I–V) characteristics PSulfone/MXene 22.5 wt% film under sunlight illumination

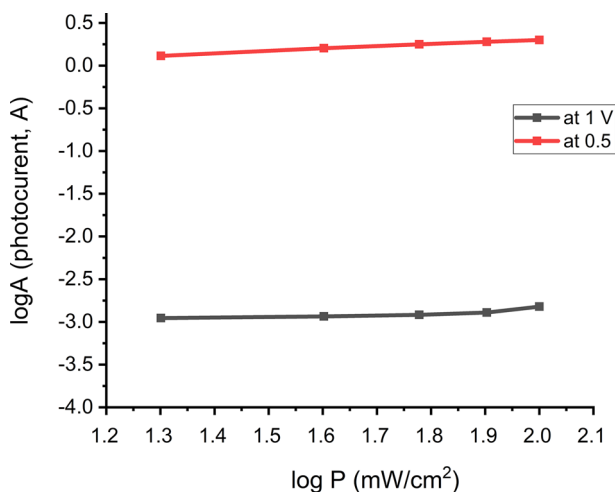


**Fig. 12** Plots of  $\log A$  versus  $\log P$  for PSulfone/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanocomposite at two different voltages

is the nanocomposite shows photoconductivity. The photocurrent increased as the light intensity increased. This proves that the photodevices show photoconductive behavior [50, 51]. When the nanocomposite was illuminated, the photocurrent suddenly increased to a certain level and there is an increase in free charge carriers and in this case photogenerated electrons contribute to the photocurrent. So, there is an increase in free charge carriers, and in this case, photogenerated electrons contribute

to the photocurrent. The dependence of the logcurrent on the logintensity of illumination for 1 and 0.5 V was estimated as  $I \sim P^{0.15}$  and  $I \sim P^{0.248}$ , respectively. The  $\log(A)$  versus  $V^{1/2}$  plots for PSulfone/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene nanocomposite films at room temperature are plotted in Fig. 13. The plots show a linear behavior with appreciable deviation from linearity at lower fields, which can be attributed to accumulation of space charge at the electrodes. The linear behavior of  $\log(A)$  versus  $V^{1/2}$  plots in the current study points to an electronic-type conduction mechanism. In the literature, it is known that charge carriers can be released from the traps to the dielectric material in doped films where the conduction mechanism is mainly the Poole–Frenkel effect [52]. This behavior may be due to the large electrical field. In other words, it shows that not much thermal energy is required for electrons to move to the conduction band. MXenes have excellent dispersibility in highly polar solvents such as DMSO, DMF and water. Therefore, for example it can easily be used with any water-soluble or dispersible polymer and with MXene, which is also water dispersible. The

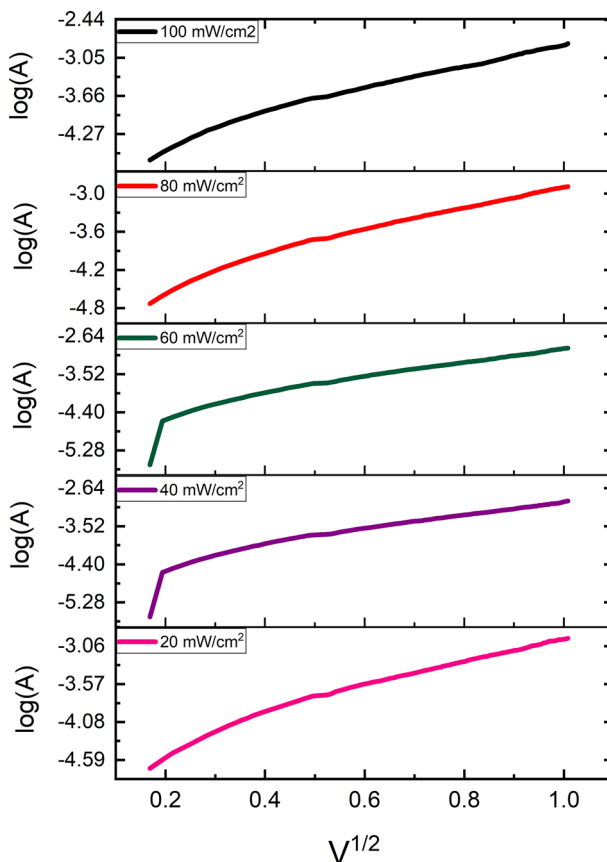


**Fig. 13** Plots of  $\log A$  versus  $V^{1/2}$  of PSulfone/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene nanocomposite at various sunlight illuminations

nanocomposite sensors obtained from mixture of MXene/polymer can be produced, especially when elastomeric polymeric materials are mixed. The polymer type contains MXene pushes toward the layers. Forms between them and this behavior cause the formation of a 3D continuous network of conductive nanosheets [53, 54].

## Conclusion

Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene nanosheet was successfully exfoliated from Ti<sub>3</sub>AlC<sub>2</sub> precursor for 48 h at 40 °C and 20% HF (v/v) solution. Thermal stability, electrical and dielectric performances of nanocomposite prepared by dispersing MXene in PSulfone matrix were comparatively investigated. MXene/PSulfone nanocomposite was fabricated to produce a nanocomposite with thermal stability and better electrical and dielectric performance. Characterization of MXene and MXene/PSulfone composite was performed by XRD, SEM, TEM, FT-IR and TGA measurements. Due to the many superior properties of MXene, the preparation of a tunable composite by adding it to the polymer matrix at different rates shows that MXene is a promising material. Based on the photocurrent generation potential of the MXene/PSulfone nanocomposite material, increasing photosensitivity will be key to the development of new, multifunctional responsive materials for many new photonic and electronic device applications. From the I–V characteristics of PSulfone/MXene, the photocurrent generation potential of PSulfone/MXene nanocomposite shows that it can be used in photodevice production.

**Acknowledgements** The authors thank TÜBİTAK for financial support from the TÜBİTAK-(122Y006) project.

**Funding** Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

1. Parodi F, (1989) Comprehensive polymer science and supplements. Pergamon Press

2. Kamal N, Kochkodan V, Zekri A, Ahzi S (2020) Polysulfone membranes embedded with halloysites nanotubes: preparation and properties. *Membranes* 10(1):1–27. <https://doi.org/10.3390/membranes10010002>
3. Gao H, Sun X, Gao C (2017) Antifouling polysulfone ultrafiltration membranes with sulfobetaine polyimides as novel additive for the enhancement of both water flux and protein rejection. *J Membr Sci* 542:81–90. <https://doi.org/10.3390/membranes10010002>
4. Zhang S, Liu Z (2011) Preparation and characterizations of polysulfone flat ultrafiltration membranes. *Adv Mat Res* 418–420:169–172. <https://doi.org/10.4028/www.scientific.net/AMR.418-420.169>
5. Athipatla V (2023) Polysulfones and their applications. *J High Sch Sci* 7(2):1–18
6. Swain SS, Unnikrishnan L, Mohanty S, Nayak SK (2022) Insight into mechanical, thermal, and chemical stability of polysulfone-based membranes for the separation of O<sub>2</sub>/N<sub>2</sub>. *Kor J Chem Eng* 39:785–797. <https://doi.org/10.1007/s11814-021-0929-7>
7. Kyriacos D. (2017) High-temperature engineering thermoplastics. Elsevier
8. Ciobanu M, Marin L, Cozan V, Bruma M (2009) Aromatic polysulfones used in sensor applications. *Rev Adv Mater Sci* 22:89–96
9. Garner SM, Cites JS, He M, Wang J (2004) Polysulfone as an electro-optic polymer host material. *Appl Phys Lett* 84(7):1049–1051. <https://doi.org/10.1063/1.1646754>
10. Nayak RJ, Khare PK, Nayak JG (2022) Study of dielectric relaxation and surface morphology of pure and malachite green doped polysulfone by dielectric and scanning electron microscope (SEM) spectroscopy. *Int J Mech Eng* 7(5):389–397
11. Badocco D, Mondin A, Pastore P, Voltolina S, Gross S (2008) Dependence of calibration sensitivity of a polysulfone/Ru(II)-tris(4,7-diphenyl-1,10-phenanthroline)-based oxygen optical sensor on its structural parameters. *Anal Chim Acta* 627:239–246. <https://doi.org/10.1016/j.aca.2008.08.019>
12. Abu-Thabit N, Umar Y, Ratemi E, Ahmad A, Abulilwi FA (2016) A flexible optical pH sensor based on polysulfone membranes coated with pH-responsive polyaniline nanofibers. *Sensors* 16:986. <https://doi.org/10.3390/s16070986>
13. Al-Hamdani AH, Kareem ZH, Al-Hamdani H (2022) Polychromatic vision improvement across the wide visual field based on polysulfones contact lens material. *NeuroQuantology* 20(8):1897–1901. <https://doi.org/10.14704/nq.2022.20.8.NQ44210>
14. Maggay IV, Yu ML, Wang DM, Chiang CH, Chang Y, Venault A (2022) Strategy to prepare skin-free and macrovoid-free polysulfone membranes via the NIPS process. *J Membr Sci* 655:120597. <https://doi.org/10.1016/j.memsci.2022.120597>
15. Tjale L, Richards H, Mahlangu O, Nthunya LN (2022) Silica nanoparticle modified polysulfone/polypropylene membrane for separation of oil-water emulsions. *Results Eng* 16:100623. <https://doi.org/10.1016/j.rineng.2022.100623>
16. Tasci RO, Kaya MA, Celebi M (2022) Hydrophilicity and flux properties improvement of high performance polysulfone membranes via sulfonation and blending with Poly(lactic acid). *High Perform Polym*. <https://doi.org/10.1177/09540083221110031>
17. Shen R, Fan T, Quan Y, Ma R, Zhang Z, Li Y, Wang Q (2022) Thermal stability and flammability of cotton fabric with TiO<sub>2</sub> coatings based on biomineralization. *Mater Chem Phys* 282:125986
18. Anasori B, Gogotsi Y (2019) 2D metal carbides and nitrides (MXenes) structure, properties and applications. Springer. <https://doi.org/10.1007/978-3-030-19026-2>
19. Sokol M, Natu V, Kota S, Barsoum MW (2019) On the chemical diversity of the MAX phases. *Trends Chem* 1(2):210–223. <https://doi.org/10.1016/j.trechm.2019.02.016>
20. Dubertret B, Heine T, Terrones M (2015) The rise of two-dimensional materials. *Acc Chem Res* 48:1–2. <https://doi.org/10.1021/ar5004434>
21. Khazaei M, Ranjbar A, Arai M, Sasaki T, Yunoki S (2017) Electronic properties and applications of MXenes: a theoretical review. *J Mater Chem C* 5:2488–2503. <https://doi.org/10.1039/C7TC00140A>
22. Guo Y, Zhou X, Wang D, Xu X, Xu Q (2019) Nanomechanical properties of Ti<sub>3</sub>C<sub>2</sub> MXene. *Langmuir* 35(45):14481–14485. <https://doi.org/10.1021/acs>
23. Wang F, Yang C, Duan C, Xiao D, Tang Y, Zhu JJ (2014) An organ-like titanium carbide material (MXene) with multilayer structure encapsulating hemoglobin for a mediator-free biosensor. *Electrochem Soc* 162(1):B16–B21. <https://doi.org/10.1149/2.0371501jes>
24. Sun Z, Xie X, Xu W, Chen K, Liu Y, Chu X, Niu Y, Zhang S, Ren C (2021) Chameleon-inspired energy-saving smart window responding to natural weather. *ACS Sustain Chem Eng* 9(38):12949–12959. <https://doi.org/10.1021/acssuschemeng.1c04413>

25. Li X, Huang Z, Shuck CE, Liang G, Gogotsi Y, Zhi C (2022) MXene chemistry, electrochemistry and energy storage applications. *Nat Rev Chem* 6:389–404. <https://doi.org/10.1038/s41570-022-00384-8>
26. Amara U, Hussain I, Ahmad M, Mahmood K, Zhang K (2023) 2D MXene-based biosensing: a review. *Small* 19(2):1–38. <https://doi.org/10.1002/sml.202205249>
27. Ling Z, Ren CE, Zhao MQ, Gogotsi Y (2014) Flexible and conductive MXene films and nanocomposites with high capacitance. *Proc Natl Acad Sci* 111(47):16676–16681. <https://doi.org/10.1073/pnas.1414215111>
28. Boota M, Anasori B, Voigt C, Zhao MQ, Barsoum MW, Gogotsi Y (2016) Pseudocapacitive electrodes produced by oxidant-free polymerization of pyrrole between the layers of 2D titanium carbide (MXene). *Adv Mater* 28:1517–1522. <https://doi.org/10.1002/adma.201504705>
29. Zhang H, Wang L, Chen Q, Li P, Zhou A, Cao X, Hu Q (2016) Preparation, mechanical and anti-friction performance of MXene/polymer composites. *Mater Des* 92:682–689. <https://doi.org/10.1016/j.matdes.2015.12.084>
30. Wu X, Hao L, Zhang J, Zhang X, Wang J, Liu J (2016) Polymer–Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> composite membranes to overcome the trade-off in solvent resistant nanofiltration for alcohol-based system. *J Membr Sci* 515:175–188. <https://doi.org/10.1016/j.memsci.2016.05.048>
31. Zhaojie Y, Minghua Z, Zhixin Z, Wenting L, Xi Z, Minmin F (2022) Application of 2D nanomaterial MXene in anion exchange membranes for alkaline fuel cells: Improving ionic conductivity and power density. *Int J Hydrogen Energy* 47(41):18122–18138
32. Amirhosein D, Ehsan S, Seyed MM, Shirin K (2022) High-performance and robust polysulfone nanocomposite membrane containing 2D functionalized MXene nanosheets for the nanofiltration of salt and dye solutions. *Desalination* 527:115600
33. Zhen S, Wei C, Hang X, Wen Y, Qing K, Ao W, Mingmei D, Juan S (2019) Fabrication of a novel antifouling polysulfone membrane with in situ embedment of Mxene nanosheets. *Int J Environ Res Public Health* 16:4659. <https://doi.org/10.3390/ijerph16234659>
34. Wang XH, Zhou YC (2010) Layered machinable and electrically conductive Ti<sub>2</sub>AlC and Ti<sub>3</sub>AlC<sub>2</sub> ceramics: a review. *J Mater Sci Technol* 26(5):385–416. [https://doi.org/10.1016/S1005-0302\(10\)60064-3](https://doi.org/10.1016/S1005-0302(10)60064-3)
35. Naguib M, Kurtoglu M, Presser V, Lu J, Niu J, Heon M, Hultman L, Gogotsi Y, Barsoum MW (2011) Two-dimensional nanocrystals produced by exfoliation of Ti<sub>3</sub>AlC<sub>2</sub>. *Adv Mater* 23:4248–4253. <https://doi.org/10.1002/adma.201102306>
36. Peng JCDYH (2022) Synthesis of MXene and its application for zinc-ion storage. *SusMat* 2:293–318
37. Chen C, Xie X, Anasori B, Sarycheva A, Makaryan T, Zhao M, Urbankowski P, Miao L, Jiang J, Gogotsi Y (2018) MoS<sub>2</sub>-on-MXene heterostructures as highly reversible anode materials for lithium-ion batteries. *Angew Chem Int Edit* 57:1846–1850. <https://doi.org/10.1002/anie.201710616>
38. Broadbelt LJ, Klein MT, Dean BD, Andrews SM (1994) Thermal stability of high performance poly(aryl ether sulfones): structure/reactivity relationships in the pyrolysis of oligomeric model compounds. *Ind Eng Chem Res* 33(10):2265–2271. <https://doi.org/10.1021/ie00034a003>
39. Broadbelt LJ, LaMarca C, Klein MT, Dean BD, Andrews SM (1995) Chemical modeling analysis of poly(aryl ether sulfone) thermal stability through computer-generated reaction mechanisms. *Ind Eng Chem Res* 34(12):4212–4221. <https://doi.org/10.1021/ie00039a009>
40. Zhang Z, Cao H, Quan Y, Ma R, Pentzer EB, Green MJ, Wang Q (2022) Thermal stability and flammability studies of MXene–organic hybrid polystyrene nanocomposites. *Polymers* 14(6):1213. <https://doi.org/10.3390/polym14061213>
41. Zheng X, Pu Z, Hu L, Tian Y, Xia J, Cheng J, Zhong J (2019) Synthesis and properties of high performance polysulfone resin with low dielectric constant and dielectric loss. *J Mater Sci: Mater Electron* 30:18168–18176. <https://doi.org/10.3390/polym14061213>
42. Yakuphanoglu F, Aydoğdu Y, Schatzschneider U, Rentschler E (2003) DC and AC conductivity and dielectric properties of the metal-radical compound: aqua [bis(2- dimethylaminomethyl-4-NIT-phenolato)]copper(II). *Solid State Commun* 128:63–67. [https://doi.org/10.1016/S0038-1098\(03\)00651-3](https://doi.org/10.1016/S0038-1098(03)00651-3)
43. Rajavel K, Luo S, Wan Y, Yu X, Hu Y, Zhu P, Sun R, Wong C (2020) 2D Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene/polyvinylidene fluoride (PVDF) nanocomposites for attenuation of electromagnetic radiation with excellent heat dissipation. *Compos Appl Sci Manuf* 129:105693. <https://doi.org/10.1016/j.compositesa.2019.105693>

44. Jin X, Wang J, Dai L, Liu X, Li L, Yang Y, Cao Y, Wang W, Wu H, Guo S (2020) Flame-retardant poly(vinyl alcohol)/MXene multilayered films with outstanding electromagnetic interference shielding and thermal conductive performances. *Chem Eng J* 380:122475. <https://doi.org/10.1016/j.cej.2019.122475>
45. Sun R, Zhang H, Liu J, Xie X, Yang R, Li Y, Hong S, Yu ZZ (2017) Highly conductive transition metal carbide/ carbonitride (MXene)/polystyrene nanocomposites fabricated by electrostatic assembly for highly efficient electromagnetic interference shielding. *Adv Funct Mater* 27(45):1–11. <https://doi.org/10.1002/adfm.201702807>
46. Gogotsi Y, Anasori B (2019) The rise of MXenes. *ACS Nano* 13(8):8491–8494. <https://doi.org/10.1021/acs.nano.9b06394>
47. Alhabeib M, Maleski K, Anasori B, Lelyukh P, Clark L, Sin S, Gogotsi Y (2017) Guidelines for synthesis and processing of two-dimensional titanium carbide ( $\text{Ti}_3\text{C}_2\text{Tx}$  MXene). *Chem Mater* 29:7633–7644. <https://doi.org/10.1021/acs.chemmater.7b02847>
48. Kim H, Kim H, Kim DW (2014) Analysis of current transport properties in nonpolar a-plane ZnO-based Schottky diodes. *J Korean Phys Soc* 65(5):751–756. <https://doi.org/10.3938/jkps.65.751>
49. Jomaa TB, Beji L, Ltaief A, Bouazizi A (2006) The current-voltage characteristics of heterostructures formed by MEH-PPV spin-coated on n-type GaAs and n-type porous GaAs. *Mater Sci Eng C* 26(2):530–533. <https://doi.org/10.1016/j.msec.2005.10.038>
50. Aslan F, Esen H, Yakuphanoglu F (2019) Electrical and photoconducting characterization of Al/coumarin: ZnO/Al novel organic/inorganic hybrid photodiodes. *J Alloys Compd* 789:595–606
51. Tataroglu A, Aydın H, Al-Ghamdi AA, El-Tantawy F, Farooq W, Yakuphanoglu F (2014) Photoconducting properties of Cd0.4 Zn0.6/p-Si photodiode by sol gel method. *J Electroceramics* 32(4):369–375
52. Abdel-Malik TG, Abdel-Latif RM, Sawaby A, Ahmed SM (2008) Electrical properties of pure and doped polyvinyl alcohol (PVA) films using gold and aluminum electrodes. *J Appl Sci Res* 4(3):331–336
53. Hossein R, Golnouth T, Masoud S (2021) MXene-based nanocomposite sensors. *ACS Omega* 6:11103–11112
54. Kateryna D, Alexander DP, Sergiy K, Kateryna S, Vladimir VB, Pawel H, Pawel Z, Tomasz NK, Piotr G, Kristina M, Vitaly B, Martin S, Maria Č, Yevheniia H, Wojciech S, Viktoriia K, Agnieszka S, Agata BG, Vitalii B, Veronika Z, Ivan B, Una R, Oleksiy G, Yury G, Maksym P (2023) Polycaprolactone–MXene nanofibrous scaffolds for tissue engineering. *ACS Appl Mater Interfaces* 15(11):14033–14047. <https://doi.org/10.1021/acsami.2c22780>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Authors and Affiliations

Kadir Demirelli<sup>1</sup>  · Esra Barim<sup>2</sup> · Aytekin Çelik<sup>3</sup> · Mustafa Yegin<sup>3</sup> · Yunus Aksoy<sup>3</sup> · Özge Hanay<sup>3</sup> · Halil Hasar<sup>3</sup>

✉ Kadir Demirelli  
kdemirelli@firat.edu.tr

<sup>1</sup> Department of Chemistry, Faculty of Science, University of Firat, Elazig, Turkey

<sup>2</sup> Vocational School of Tunceli, University of Munzur, 62000 Tunceli, Turkey

<sup>3</sup> Department of Environmental Engineering, Faculty of Engineering, Firat University, 23119 Elazig, Turkey