



The Effect of Mxene on Antibacterial Activity and its Optical Characterization for Biological Application

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Abstract

MXene was synthesized from the Ti_3AlC_2 MAX phase via hydrothermal wet chemical etching using a hydrofluoric acid-hydrochloric acid mixture. X-ray diffraction showed a shift of the (002) peak to lower 2θ values, indicating expanded interlayer spacing after selective removal of aluminium and surface termination. Scanning electron microscopy revealed the characteristic accordion-like, multilayer morphology of exfoliated MXene, while energy-dispersive X-ray spectroscopy confirmed aluminium depletion and the presence of $-\text{F}$, $-\text{O}$, and $-\text{OH}$ terminations. Raman and UV-visible-near-infrared spectroscopy verified retained structural integrity and strong broadband optical absorption of the delaminated nanosheets. These observations demonstrate successful etching and exfoliation into high-quality, stable $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets with well-defined structural and surface characteristics. Antibacterial testing showed improvement for MXene versus MAX. Ti_3AlC_2 gave 14 mm inhibition, $\sim 58\%$ of Nitrofurantoin's 24 mm. $\text{Ti}_3\text{C}_2\text{T}_x$ MXene yielded 26 mm, $\sim 8\%$ above the antibiotic and 85% higher than Ti_3AlC_2 . Efficacy is attributed to higher surface reactivity and sharper nanosheet edges improving membrane interaction. Thus, $\text{Ti}_3\text{C}_2\text{T}_x$ combines optical robustness and superior antibacterial performance, promising for antimicrobial coatings and biomedical environmental applications. The study adds to growing evidence that MXenes, with mechanisms involving physical damage and oxidative stress, can serve as effective antimicrobial agents.

Keywords: Hydrothermal Wet Chemical Etching; Antibacterial Activity; Confocal Raman Spectra

Abbreviations

HF: Hydrofluoric Acid; MQWs: Multiple Quantum Wells; MILD: Minimally Intensive Layer Delamination; LPE: Liquid-phase Exfoliation; HF: Hydrogen Fluoride; XRD: X-ray Diffractometer; SEM: Scanning Electron Microscopy; EDS: Energy Dispersive X-ray Spectroscopy; MTCC: Microbial Type Culture Collection Centre.

Introduction

Among the rapidly growing family of nanomaterials, two-dimensional (2D) transition metal carbides and nitrides—collectively referred to as MXenes—have garnered significant attention since their discovery in 2011 [1]. MXenes are typically synthesized by selectively etching the “A” layer from their three-dimensional MAX

phase precursors ($M_{n+1}AX_n$), where M represents an early transition metal, A is an element from groups 13 or 14, and X is either carbon or nitrogen. This top-down synthesis strategy results in 2D layered structures with the general formula $M_{n+1}X_nT_x$, where T_x denotes surface terminations such as $-OH$, $-F$, $-O$, or $-Cl$, which arise during the etching process [2]. $Ti_3C_2T_x$ MXene, derived from the Ti_3AlC_2 MAX phase, is one of the most widely studied members of the MXene family due to its exceptional electrical conductivity, hydrophilicity, high mechanical strength, and rich surface chemistry. These properties make it highly suitable for applications in energy storage devices (e.g., lithium-ion batteries and supercapacitors), electromagnetic shielding, water purification, electrocatalysis, sensors, and biomedical technologies [3-5]. Furthermore, its optical and electronic properties have made it a candidate material for use in next-generation optoelectronic and photothermal devices [3]. The synthesis of high-quality $Ti_3C_2T_x$ MXene, however, poses several challenges. Traditional methods rely on hazardous chemicals such as hydrofluoric acid (HF) to etch away the Al layers from the MAX phase. While effective, the use of HF presents significant health, safety, and environmental concerns and can introduce defects that negatively affect the material's performance [1]. Consequently, research has expanded toward developing alternative synthesis strategies, including in situ HF generation via HCl - LiF or NH_4F systems, solid-state routes, and eco-friendly hydrothermal techniques [6-8]. Optimization of etchant composition, temperature, reaction time, and post-treatment methods plays a crucial role in determining the final MXene quality, yield, surface chemistry, and stability. Recent studies have demonstrated that modifying synthesis parameters can lead to tunable surface functionalities, improved electrical properties, and enhanced oxidation resistance, thereby broadening the scope of $Ti_3C_2T_x$ MXene applications [9]. A flexible and wearable capacitive pressure sensor has been fabricated based on the unique honeycomb weave architecture [10]. A multiple quantum wells (MQWs) has enhanced the light absorption capability in phototransistors [11]. An optimised used of hydrofluoric acid/ HCl etching method, produces $Ti_3C_2T_x$ with minimal concentration of defects for biological applications [12]. Moreover, emerging methods such as lithium chloride-assisted delamination, minimally intensive layer delamination (MILD), and liquid-phase exfoliation (LPE) have enabled the production of few-layer or quantum dot forms of MXene with unique optoelectronic behavior [13,14]. According to Wang H, et al. [15] performed a comprehensive Raman and optical analysis of $Ti_3C_2T_x$ synthesized via HF, $LiF+HCl$, and TMAOH routes, clearly revealing how etching chemistry and surface terminations ($-O$, $-F$, $-OH$) induce measurable shifts in both Raman and UV-Vis spectra. By Sarycheva A [16] demonstrated that even within HF/ HCl synthesis, small variations in etching ratio or delamination process significantly alter the $A_{1g}(C)$ Raman

mode ($720-736\text{ cm}^{-1}$) and the visible plasmonic absorption band near 550 nm, directly linking synthesis parameters to optical response. It has been theoretically predicted and experimentally confirmed that the plasmonic absorption shift is a direct function of surface termination type and electronic structure modification by Asma Eskandarli [17]. Recently Mxene has been used as ink by water as a solvent [18]. Since the discovery of MXenes have attracted significant attention due to their exceptional electrical conductivity, hydrophilicity, large surface area, and highly tunable surface chemistry, all of which enable versatile interactions with biological systems. Recent reviews highlight that these unique physicochemical properties make MXenes particularly suitable for applications such as drug delivery, photothermal therapy, biosensing, tissue engineering, and antimicrobial treatments. In the biomedical context, MXene-based nanocomposites have demonstrated strong potential in enhancing cell labeling, imaging, and therapeutic efficiency, owing to their ability to be functionalized with a wide range of biomolecules and therapeutic agents. Their high photothermal conversion efficiency and biocompatibility further support their use in cancer therapy and antibacterial photothermal treatments, while their conductive nature enables advanced electrochemical biosensors for disease diagnostics [19]. As research progresses, MXenes continue to evolve as multifunctional materials capable of integrating diagnostic and therapeutic (theranostic) capabilities, positioning them at the forefront of next-generation biomedical technologies [20,21]. Given the rapid growth of MXene research and its remarkable potential across diverse technological domains, this study seeks to provide a comprehensive overview of the latest advances in the synthesis and characterization of $Ti_3C_2T_x$ MXene. Particular emphasis is placed on recent strategies aimed at optimizing synthesis methods to improve material quality, scalability, and environmental sustainability. Furthermore, the development of optically stable MXenes with enhanced antibacterial properties paves the way for their application in antibacterial coatings and other biological applications.

Materials and Methods

Titanium aluminium carbide (Ti_3AlC_2) with purity of 99 % and molecular weight of 194.60 g/mol, hydrochloric acid (HCl) and hydrogen Fluoride (HF) were purchased from Sigma Aldrich and used as bought without further purification. The selective etching of Ti_3AlC_2 to synthesize multilayer $Ti_3C_2T_x$ MXene was carried out using a conventional hydrothermal method [22]. An etchant solution was prepared by mixing 16 mL of 40% aqueous HF with 24 mL of 12 M hydrochloric acid (HCl) in a Teflon-lined container. The solution was stirred at 300 rpm for 10 minutes at room temperature to ensure homogeneous mixing. Subsequently, 0.5 g of Ti_3AlC_2 powder was gradually added to the etchant under continuous

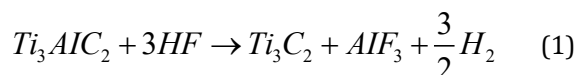
stirring to avoid sudden exothermic reactions. The etching process was maintained at room temperature for 48 hours with constant stirring at 500 rpm. Upon completion, the mixture was centrifuged at 3500 rpm to separate the etched product, followed by repeated washing with deionized (DI) water until the pH of the supernatant reached neutral (pH $\approx$ 7), indicating the removal of residual acids. The resulting sediment was collected, transferred into a crucible, and dried under vacuum at 60 °C for 24 hours. After drying, the solid product was manually ground using a mortar and pestle to obtain the final multilayer $Ti_3C_2T_x$ MXene powder suitable for further characterization and application.

The structural properties and crystallite-size of the samples were determined by Seifert X-ray diffractometer (XRD) using Cu-K α radiation (1.5406 Å). Morphology of the nanopowders was studied by Scanning Electron Microscopy (SEM), traces of elements were identified using Energy Dispersive X-ray Spectroscopy (EDS) (elements down to Boron) (HORIBA EX-450). Spectrophotometer (Model: Varian CARY 5E UVeVIS NIR) was employed to record the UV-VIS optical spectra of the samples. Confocal Raman Spectra (Model: BRUKER RFS 27) were recorded to determine the

lattice dynamics of the particles with the spectral range of 4000-50 cm^{-1} with Nd: YAG (1064 nm) laser source. Optical image of particle under confocal Raman spectroscopy (Model: The Perkin Elmer Spectrum) spectra were recorded using the KBr pellet technique in the 4000- 450 cm^{-1} frequency range. The Bacterial strains of *Vibrio cholera*, *Vibrio parahaemolyticus*, *Aeromonas hydrophila* and *Pseudomonas* were obtained from Microbial Type culture Collection Centre (MTCC), Chandigarh. Chemical Etching with Hydrofluoric Acid (HF).

Process: Immersion of MAX phase powder (e.g., Ti_3AlC_2) in concentrated HF (10–50%) at 25–40 °C for 24–48h followed by washing and centrifugation to neutral pH.

Reaction:



Produces multilayer $Ti_3C_2T_x$ with OH and F surface terminations. High chemical efficiency but hazardous handling due to HF toxicity [23] Figure 1.

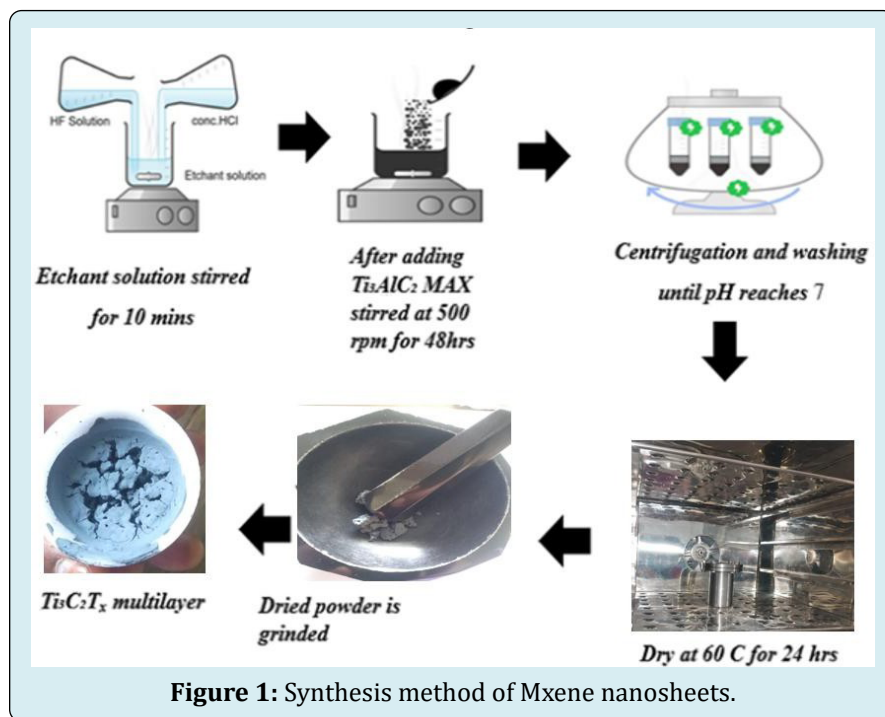


Figure 1: Synthesis method of Mxene nanosheets.

Result

Structural Analysis

The X-ray diffraction (XRD) patterns of pristine Ti_3AlC_2 and multilayer $Ti_3C_2T_x$ MXene are presented in Figure 2. The diffraction peaks at 2θ values of 9.5°, 19.1°, 33.9°, 36.7°, 39.1°, 41.7°, 48.2°, 56.4°, 60.1°, 65.4°, 70.2°, and 73.9° correspond to the (002), (004), (101), (103), (104), (105), (107), (109), (110), (111), (112), and (118) planes, respectively, of the crystalline Ti_3AlC_2 phase, in agreement with the JCPDS card no. 52-0875 [24]. Among these, the (002) and (104) reflections are of particular significance in monitoring the transformation of Ti_3AlC_2 to MXene during

36.7°, 39.1°, 41.7°, 48.2°, 56.4°, 60.1°, 65.4°, 70.2°, and 73.9° correspond to the (002), (004), (101), (103), (104), (105), (107), (109), (110), (111), (112), and (118) planes, respectively, of the crystalline Ti_3AlC_2 phase, in agreement with the JCPDS card no. 52-0875 [24]. Among these, the (002) and (104) reflections are of particular significance in monitoring the transformation of Ti_3AlC_2 to MXene during

the selective etching process. A critical indicator of successful MXene formation is the shift of the (002) peak to a lower 2θ angle, which signifies an increase in the interlayer spacing (d-spacing) due to the removal of Al atoms and intercalation of surface terminations. After etching, the (002) peak shifts from 9.5° to approximately 8.4° , indicating the exfoliation and delamination of the $\text{Ti}_3\text{C}_2\text{T}_x$ layers [25]. Concurrently, the persistence MXene of the (104) peak suggests partial removal of Al from the MAX phase [26]. The appearance of a peak at $2\theta \approx 60^\circ$, corresponding to the (110) plane, further supports the presence of a well-ordered layered MXene structure. Additional shifts in the (004) and (103) peaks toward lower angles also corroborate the expansion in the lattice spacing following the introduction of surface functional groups [27]. Residual diffraction peaks such as (101) and (109) may be attributed to unreacted Ti_3AlC_2 or residual etchants such as HF or HCl trapped within the structure [14]. A magnified view of the (002) peak, shown in Figure 3 clearly illustrates the shift to a lower angle, confirming the expansion of basal planes in the $\text{Ti}_3\text{C}_2\text{T}_x$ structure. This structural expansion is commonly associated with the substitution of Al atoms by oxygen-and/or fluorine-containing surface terminations, which increase interlayer repulsion and promote delamination [28]. The average crystallite size in the (002) direction was estimated using the Scherrer equation, yielding a value of approximately 9.16 nm after exfoliation. These XRD results provide compelling evidence for the successful etching and exfoliation of MXene sheets, confirming both the removal of Al and the structural reconfiguration of the material into its characteristic two-dimensional layered form. Overall, XRD serves as a critical tool for tracking the synthesis process, assessing the degree of exfoliation, and determining the structural evolution of MXene nanosheets.

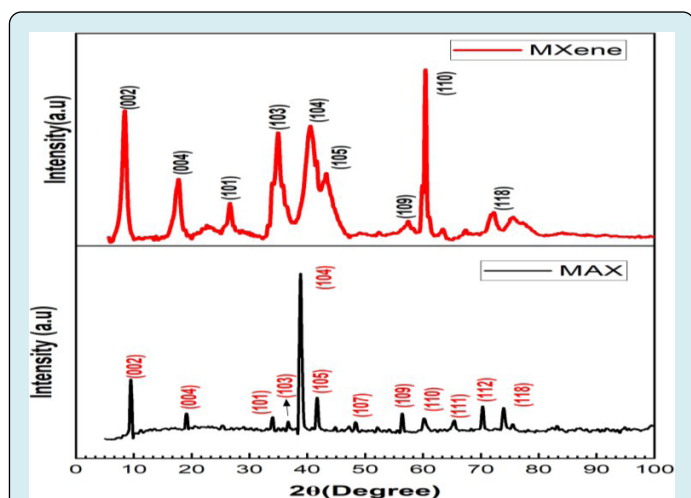


Figure 2: XRD patterns of Ti_3AlC_2 MAX phase and $\text{Ti}_3\text{C}_2\text{T}_x$ multilayer.

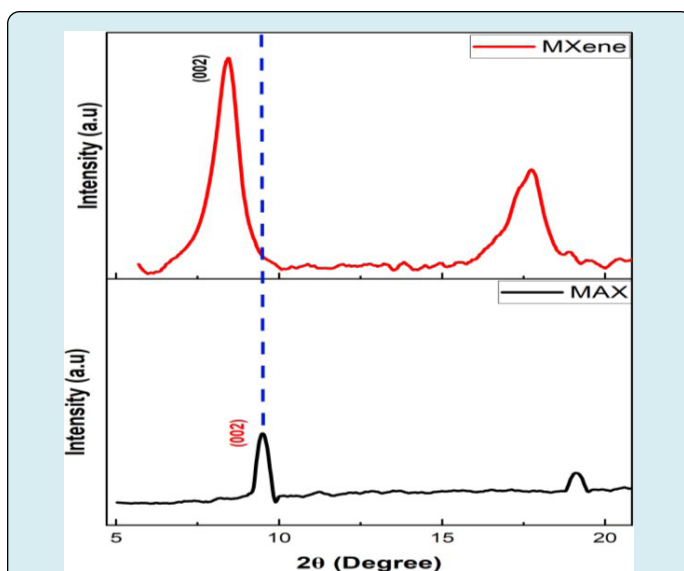


Figure 3: XRD pattern of MXene at (002) peak position.

Morphological and Elemental study

The morphology of the synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ multilayer MXene was examined using scanning electron microscopy (SEM), as presented in Figure 4 (a-d). The micrograph clearly reveals a stacked, lamellar structure with a pronounced accordion-like appearance, characteristic of multilayered MXene formed through selective etching of the aluminum (Al) layer from the Ti_3AlC_2 MAX phase. The observed broadening of the interlayer spacing and the discernible separation between individual sheets provide direct evidence of effective chemical exfoliation, although the product predominantly remains in a multilayered, non-delaminated configuration. These features are consistent with partial exfoliation, wherein intercalation and surface termination occur without complete delamination [29]. Energy-dispersive X-ray spectroscopy (EDAX), shown in Figure 4 and Table 1, further confirmed the elemental composition of the synthesized material. The spectrum and elemental mapping indicated a high atomic percentage of titanium (Ti, 31.35 at.%) and carbon (C, 34.06 at.%), consistent with the stoichiometry of Ti_3C_2 . The presence of fluorine (F, 18.13 at.%), oxygen (O, 13.59 at.%), and chlorine (Cl, 1.98 at.%) suggests the successful introduction of surface termination groups ($-\text{F}$, $-\text{O}$, and $-\text{Cl}$), which typically arise from the use of HF/HCl during the etching process. A trace amount of residual aluminum (Al, 0.89 at.%) implies that the majority of the Al from the parent MAX phase was effectively removed during etching [30]. Figure 6 illustrates the EDS layered image of spatial distribution of the elements, where titanium is highlighted in red, carbon in pink, fluorine in blue, and chlorine in green. This layered elemental representation reinforces the uniformity of surface functionalization and confirms the integrity of the synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ structure.

Taken together, the SEM and EDAX analyses validate the successful synthesis of multilayer MXene with well-defined morphology and surface chemistry, essential for its

performance in advanced material applications [31] (Figures 5 & 6).

Element	Line Type	Weight %	Weight % Sigma	Atomic %
C	K series	15.94	0.84	34.06
O	K series	8.47	1.08	14.48
F	K series	13.42	0.65	18.13
Cl	K series	2.74	0.11	1.98
Ti	K series	58.5	1	31.35
Total		100		100

Table 1: Elemental composition of Mxene.

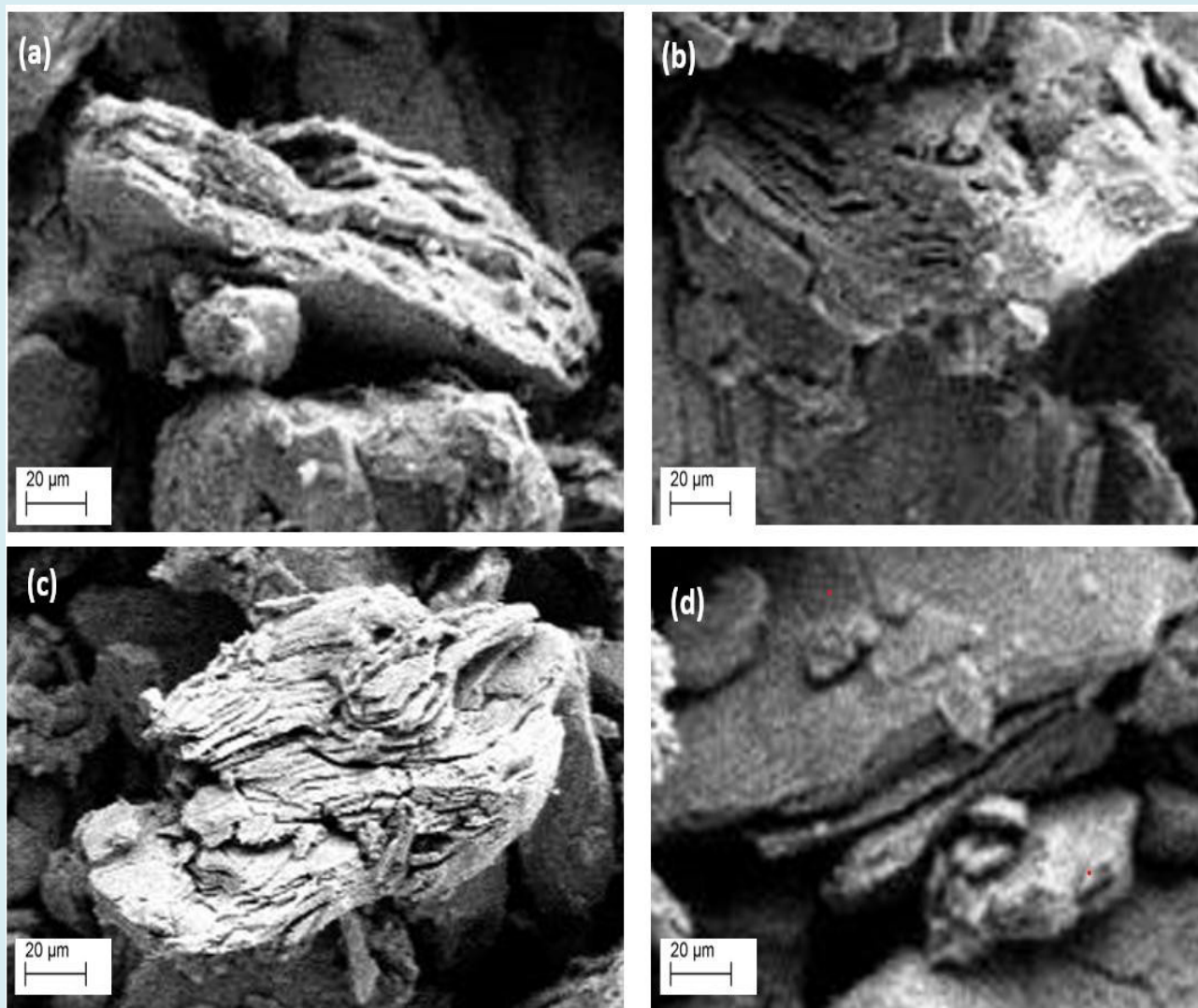


Figure 4: SEM images of $Ti_3C_2T_x$ Nano sheets.

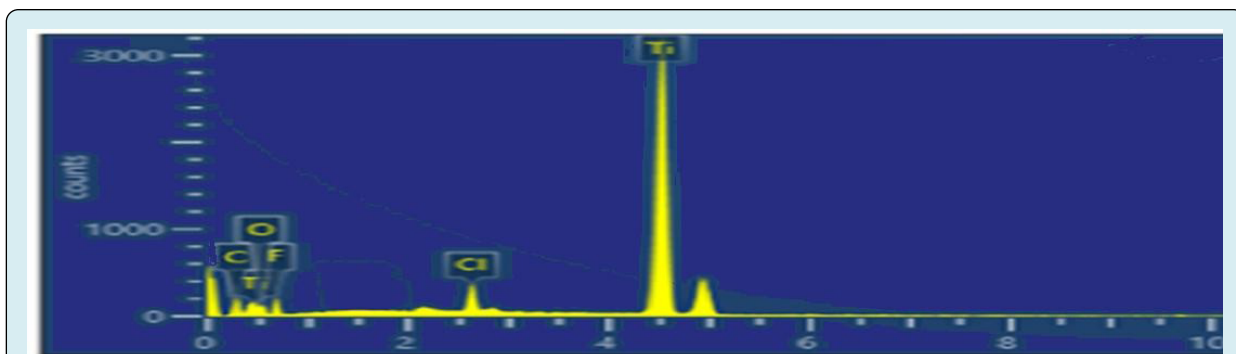


Figure 5: EDAX spectra of $\text{Ti}_3\text{C}_2\text{T}_x$.

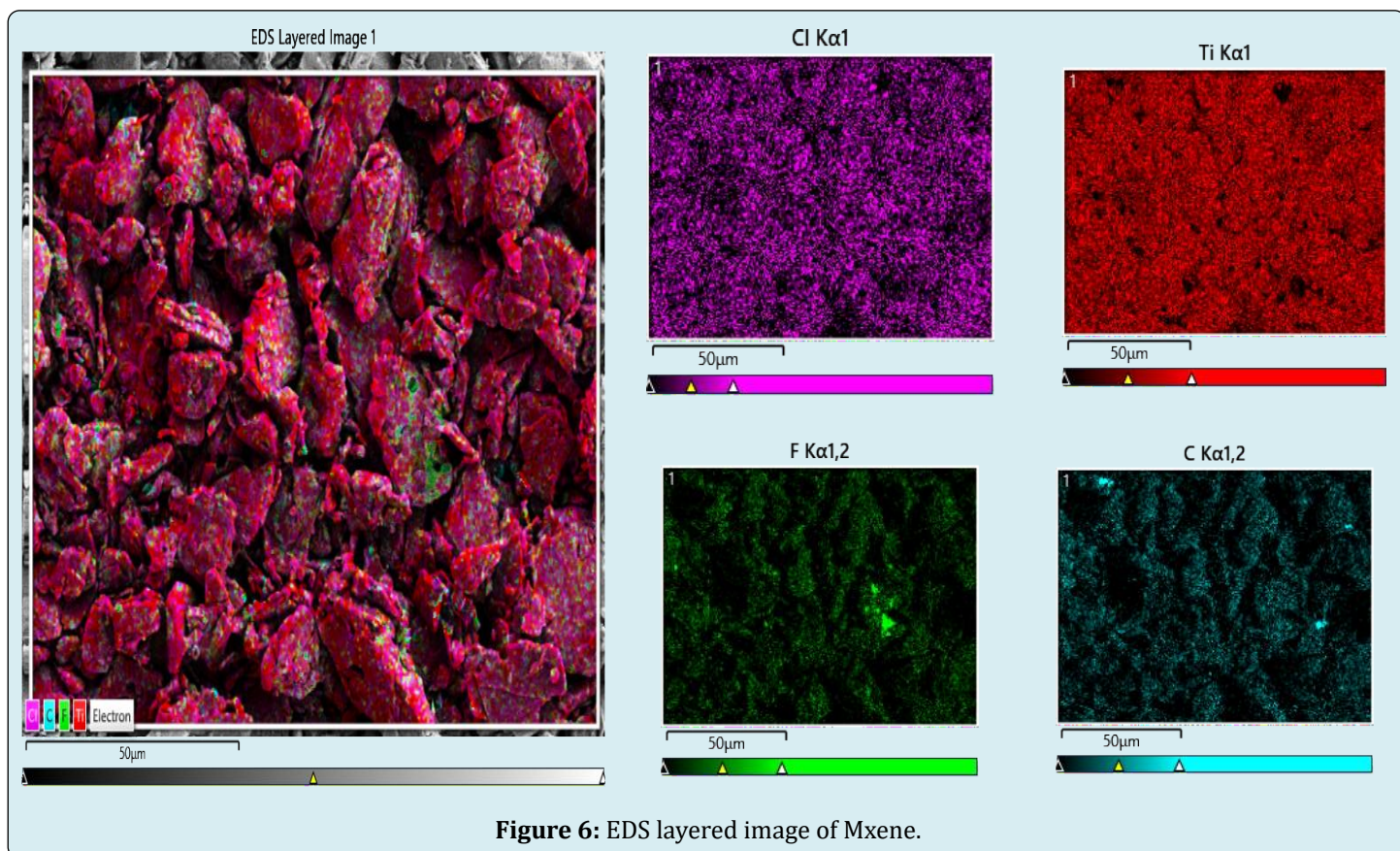


Figure 6: EDS layered image of MXene.

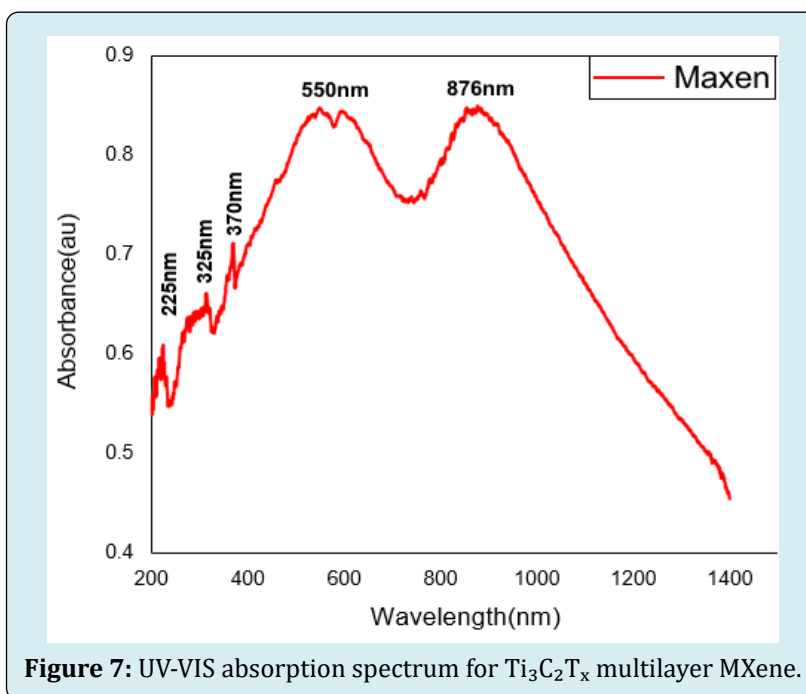
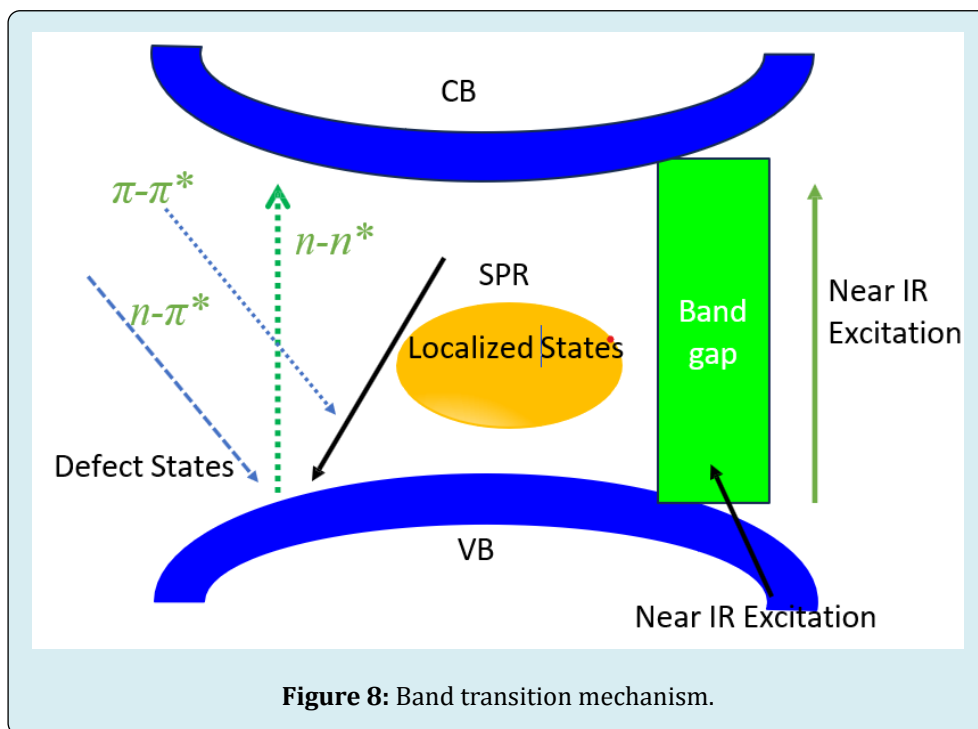
Optical Studies

The UV-Vis-NIR absorbance spectrum of the synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ multilayer MXene, measured across the 200–1400 nm wavelength range, reveals multiple distinctive absorption features, as depicted in Figure 7. A sharp peak at 225 nm is attributed to π - π^* electronic transitions within Ti-C bonds, indicating the presence of sp^2 hybridized carbon layers inherent to the MXene architecture [32]. Additional broader peaks centered around 325 nm and 370 nm correspond to n - π^* transitions, most likely involving oxygen-containing

surface terminations such as -OH and -O groups, introduced during the HF/HCl etching process [33]. A prominent broad absorbance centered around 550 nm is indicative of surface plasmon resonance (SPR), reflecting the collective oscillations of free electrons and suggesting metallic conductivity. This feature is characteristic of MXene multilayers and supports the assertion of successful exfoliation and high electronic conductivity [34]. Figure 8 and Table 2 shows the corresponding band transition interpretation. Furthermore, a second broad peak appears near 876 nm within the near-infrared (NIR) region. This is often linked to interband

transitions and localized surface or defect states, originating from multilayer stacking and functional group incorporation during synthesis [35]. The extended broad absorption from the ultraviolet through the NIR range illustrates robust light-matter interaction, further confirming the semi-metallic nature of the synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. Collectively,

these spectral characteristics not only affirm the successful synthesis and functionalization of MXene nanosheets but also underscore their potential for optoelectronic, sensing, and photonic device applications, due to their tunable optical and electronic properties [36].



Transition Type	Wavelength Range	Origin	Implication
$\pi-\pi^*$ transition	~ 225 nm	Electronic transitions within Ti-C bonds (sp^2 hybridized carbon)	Indicates graphitic domains and strong in-plane bonding.
$n-\pi^*$ transitions	$\sim 325-370$ nm	Lone-pair electrons from -OH, -O surface terminations	Confirms surface functionalization via HF/HCl etching.
Surface Plasmon Resonance (SPR)	~ 550 nm	Collective oscillation of free electrons	Reflects metallic conductivity and multilayer exfoliation.
Interband/Defect Transitions	~ 876 nm (NIR)	Localized states from stacking faults, defects, and functional groups	Suggests semi-metallic nature and tunable optoelectronic behavior

Table 2: Breakdown of Optical Transitions in MXene.

The Raman spectra of the etched $Ti_3C_2T_x$ MXene are presented in Figure 9. Key peaks observed at 269, 423, and 613 cm^{-1} are associated with vibrations from Ti_3AlC_2 , specifically attributed to shear and longitudinal oscillations of the Ti and Al atoms [37,38]. The peak at 269 cm^{-1} , corresponding to Al vibrations, disappears in the MXene spectrum, signifying the successful etching and removal of Al atoms, resulting in the formation of the $Ti_3C_2T_x$ MXene structure [39]. Additionally, two broad peaks at 1353 cm^{-1} and 1571 cm^{-1} are identified as the D and G bands of carbon. The intensity of the D band indicates defects and disorder. The ratio of ID/IG ratio of 0.95 indicates defects [40]. These peaks are indicative of the presence of carbon in the material and suggest that disorder exists within the carbon structure [41]. The intensity of these peaks confirms the exposure of more carbon surfaces during the etching process [42]. The G

peak, at 1571 cm^{-1} , is associated with the stretching of C-C bonds in sp^2 hybridized carbon atoms, typically observed in chain-like or spring structures [43], whereas the D peak at 1353 cm^{-1} occurs in disordered sp^2 carbon rings [44]. Further peaks at 387 cm^{-1} and 625 cm^{-1} correspond to Ti-C bond vibrations, while the peak at 204 cm^{-1} is attributed to the out-of-plane vibrations of Ti and C atoms [45]. Notably, an intense peak around 153 cm^{-1} is observed, which may be due to the increased laser power during the measurement, leading to the formation of oxidized Ti_3C_2 [46-48]. The optical images shown in Figure 10, captured under confocal Raman spectroscopy at $200\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$ scales, reveal the characteristic flake-like morphology of the MXene sheets. These images confirm the successful etching process and the formation of $Ti_3C_2T_x$ MXene nanoflakes.

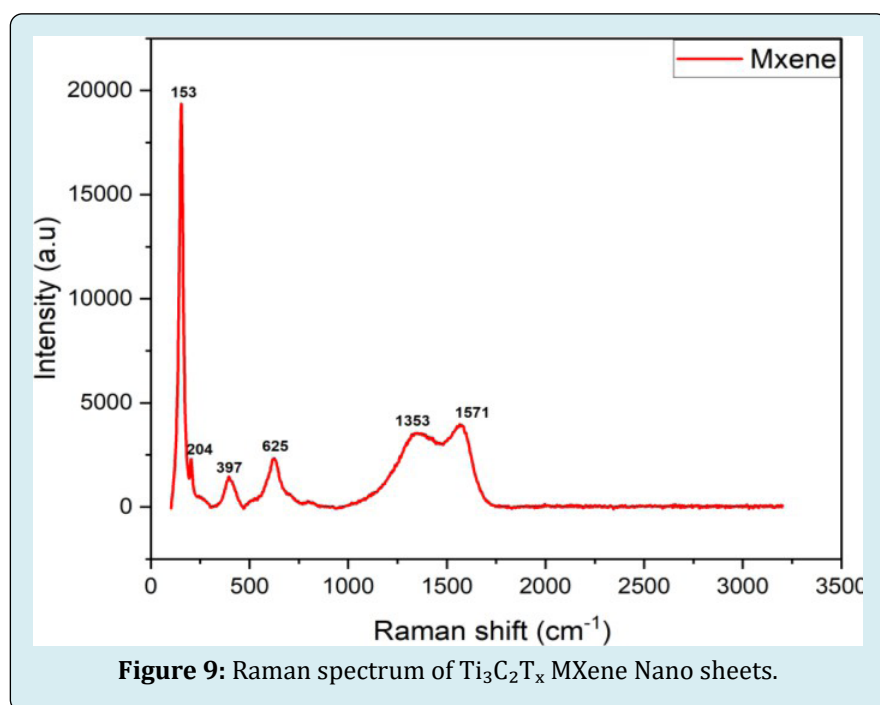


Figure 9: Raman spectrum of $Ti_3C_2T_x$ MXene Nano sheets.

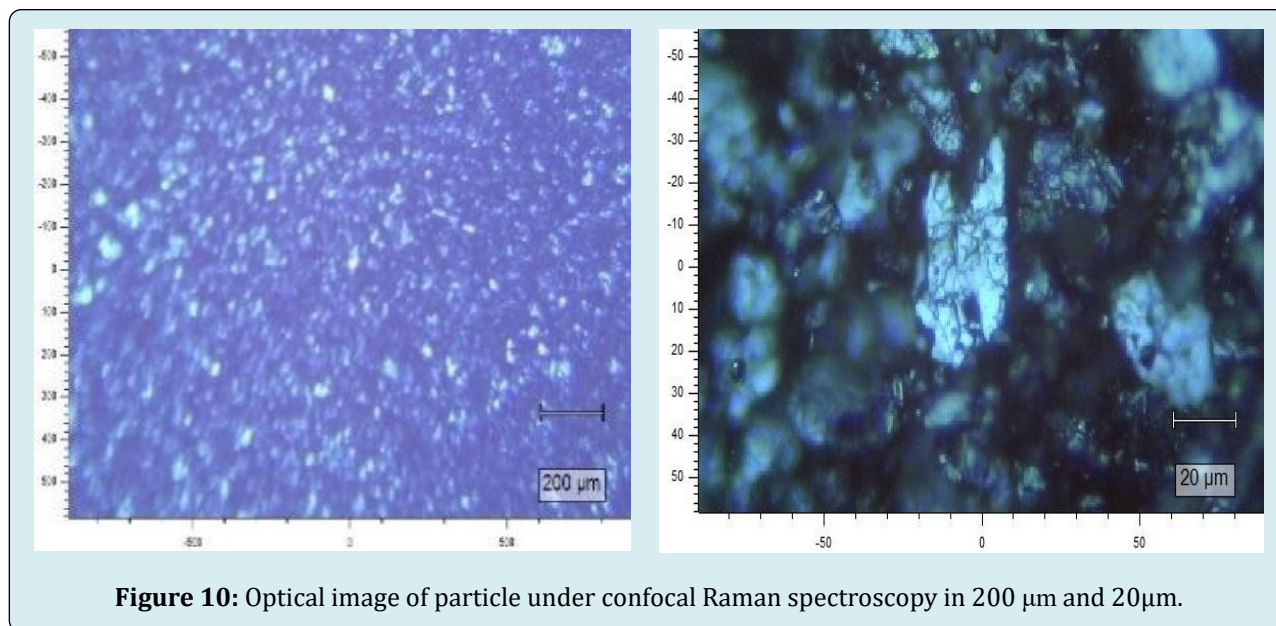


Figure 10: Optical image of particle under confocal Raman spectroscopy in 200 μm and 20 μm .

Antibacterial Assay

Antibacterial activity test in Figure 11 was carried out following the modification of the method originally described by Deysher G, et al. [49] for the samples. Muller Hinton agar was prepared and autoclaved at 15 lbs pressure for 20 minutes and cooled to 45°C. The cooled media was poured on to sterile petri plates and allowed for solidification. The plates with media were seeded with the respective microbial suspension using sterile swab. The various solvents such as Acetone, Methanol, Ethanol extracts discs were prepared and individually placed on each petri plates also placed control and standard Nitrofurantoin (300 μg) for Bacteria discs. The plates were incubated at 37°C for 24 hrs. After incubation period, the diameter of the zone formed around the paper disc were measured and expressed in mm. Table 3 indicates the corresponding activity of the mxene with Max phase. Figure 12 clearly demonstrates the antibacterial assay statistical variation of both Ti_3AlC and Mxene. Sample S2 (MXene) exhibited significantly stronger antibacterial activity against *Escherichia coli* than S1 (Ti_3AlC_2), as evidenced by its larger zone of inhibition (26 mm vs. 14 mm), aligning with prior studies on MXene-based antimicrobial mechanisms. The antimicrobial efficacy of MXene samples S1 and S2 was evaluated using the agar well diffusion method, a standard technique for assessing antibacterial potency. The measured zones of inhibition—14 mm for S1 and 26 mm for S2—indicate a marked difference in their ability to suppress *E. coli* growth. This disparity suggests that S2 possesses superior antibacterial properties, which may be attributed to a higher concentration of active MXene material, improved surface functionalization, or enhanced physicochemical interactions with bacterial

membranes. MXenes are two-dimensional transition metal carbides known for their sharp edges, high surface area, and tunable surface chemistry, all of which contribute to their antimicrobial behavior. According to studies published in Bauer AW, et al. [50], MXenes exert antibacterial effects through multiple mechanisms, including physical disruption of bacterial membranes, oxidative stress induction, and ion release. These mechanisms are particularly effective against Gram-negative bacteria like *E. coli*, which possess an outer membrane that can be compromised by MXene nanosheets. The enhanced performance of S2 may also reflect differences in synthesis parameters, such as etching conditions, interlayer spacing, or terminal group composition (e.g., $-\text{OH}$, $-\text{F}$, $-\text{O}$), which influence MXene dispersion and interaction with microbial cells. As demonstrated in comparative studies, MXenes with optimized surface terminations and higher colloidal stability tend to exhibit stronger antibacterial activity. Figure 13 represents the Antibacterial Mechanisms of MXene Nanosheets. Their multifaceted mechanisms of action combine physical, chemical, and photothermal effects, offering a synergistic approach to microbial inhibition that is distinct from conventional antibiotics. The first mechanism involves physical damage and intercalation. Owing to their sharp edges and layered morphology, MXene nanosheets can mechanically disrupt bacterial cell membranes, leads to leakage of intracellular contents and eventual cell lysis. Furthermore, their intercalative capacity allows ions and molecules to penetrate bacterial envelopes, destabilizing structural integrity and impairing essential cellular functions. A second, equally critical mechanism is oxidative stress through reactive oxygen species (ROS) generation. Surface defects on MXene sheets facilitate electron transfer reactions with oxygen or hydroquinone, resulting in the formation of

ROS such as hydroxyl radicals ($\bullet\text{OH}$) and hydrogen peroxide (H_2O_2). These highly reactive species induce oxidative damage to proteins, lipids, and nucleic acids, thereby compromising bacterial metabolism and viability. The ability of MXenes to amplify ROS production underscores their chemical potency in antibacterial applications. The third mechanism encompasses photothermal and chelation effects. MXenes exhibit strong photothermal conversion, efficiently transforming incident light into localized heat. This thermal stress is sufficient to denature bacterial proteins and disrupt cellular processes. In parallel, MXenes can chelate essential metal ions, depriving bacteria of nutrients required

for growth and survival. The combination of heat shock and nutrient deprivation further enhances antibacterial efficacy. Collectively, these mechanisms highlight the versatility of MXene nanosheets as antibacterial agents. Their integration of mechanical disruption, oxidative stress, and photothermal responses positions them as promising candidates for biomedical applications, including wound healing, implant coatings, and water purification technologies. Future research should focus on optimizing MXene structures to maximize antibacterial efficiency while ensuring biocompatibility.

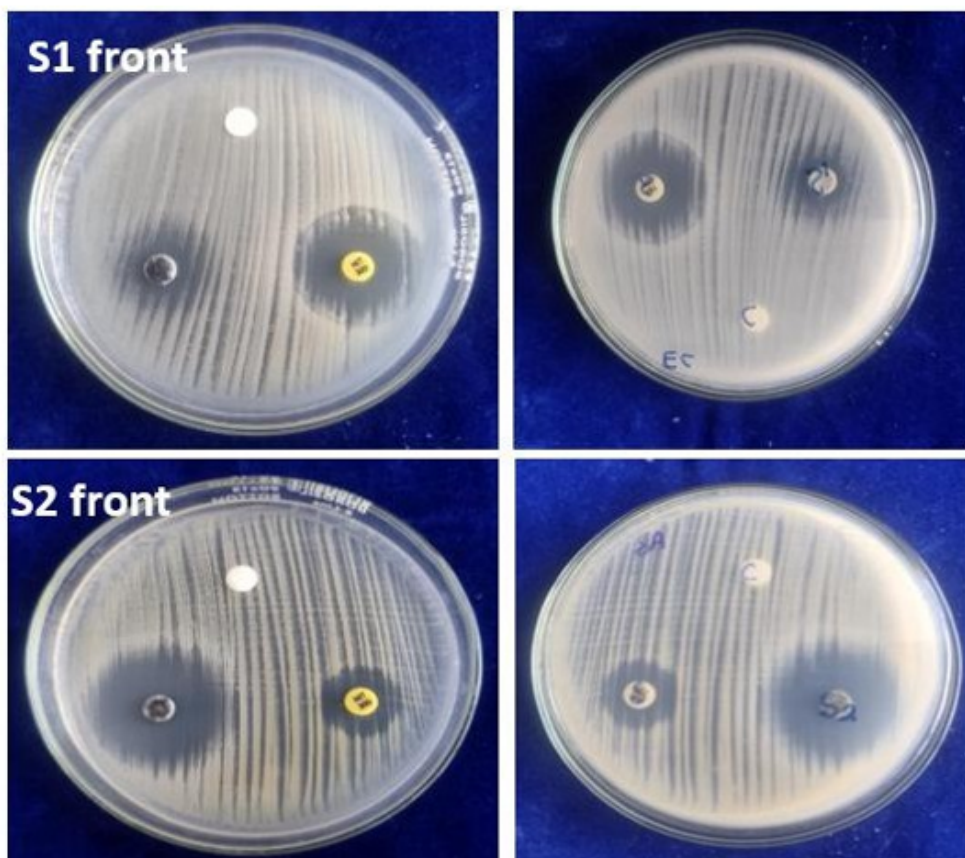
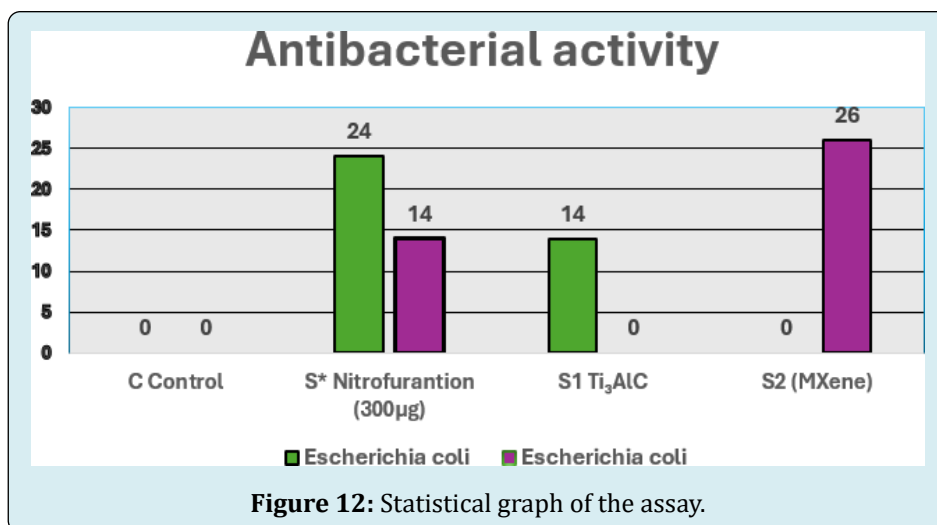
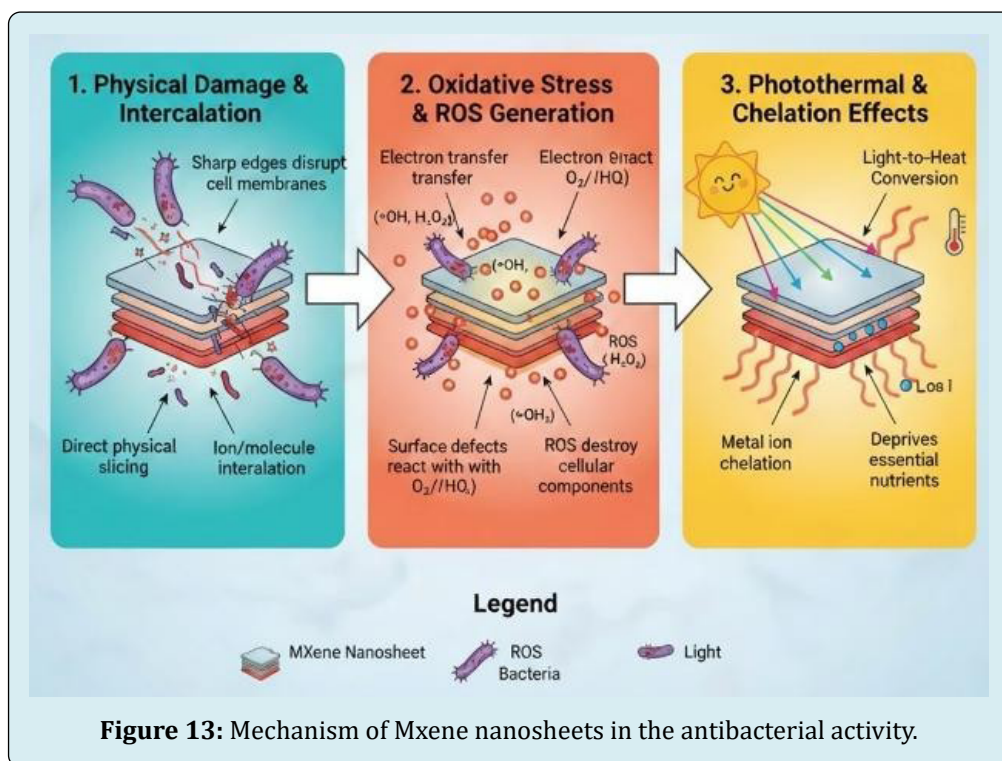


Figure 11: Concentration dependent antibacterial activities of of $\text{Ti}_3\text{Al C}_2$ (S1) and Mxene (S2) onto E.Coli and Nitrofurantion bacterial cells.

Sl.No	Bacteria	Zone of Inhibition (mm in Diameter)			
		C Control	S* Nitrofurantion (300 μg)	S1 Ti_3AlC	S2 (MXene)
1	Escherichia coli	-	24	14	-
2	Escherichia coli	-	14	-	26

C-Control; S*- Nitrofurantion (300 μg)

Table 3: Assay of Anti-Bacterial Activity.



Conclusion

Ti₃AlC₂ MAX phase can be effectively converted into Ti₃C₂T_x MXene via wet chemical etching with HF/HCl, yielding multilayer nanosheets with expanded interlayer spacing and the expected accordion-like morphology. XRD confirmed the structural transformation by a clear shift of the (002) peak to lower 2θ values, while SEM and optical imaging verified successful exfoliation into characteristic layered flakes. EDAX analysis further showed removal of aluminium and presence of surface terminations such as -F, -O, and -OH, and Raman and UV-Vis-NIR spectroscopy confirmed structural integrity and broad optical absorption—features consistent with high-

quality MXene nanosheets. Antibacterial assays revealed a marked enhancement in activity upon transformation from MAX phase to MXene. Ti₃AlC₂ produced a moderate inhibition zone of 14 mm, about 58% of the standard antibiotic Nitrofurantoin's effect, whereas MXene exhibited a 26 mm inhibition zone, surpassing the antibiotic benchmark by roughly 8% and showing an 85% increase over Ti₃AlC₂. These results underscore that the etching-exfoliation process not only yields structurally well-defined MXene but also significantly amplifies antimicrobial efficacy, likely due to increased surface reactivity and sharp nanosheet edges that enhance interactions with bacterial membranes. Collectively, the structural, optical, and antibacterial findings

demonstrate that the synthesized MXene is a promising candidate for antimicrobial coatings and biomedical or environmental applications that demand microbial control.

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CRedit authorship contribution statement

Sivasankari J: Conceptualization, Investigation, Methodology, Data curation, Writing – original draft.
Pavithra A: Resources, Formal analysis, Writing – review & editing.

Declaration of Competing 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. Data availability Materials, data, and associated protocols are available to readers without undue qualifications regarding material transfer agreements.

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