MXene Materials for Biomedical Applications

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Additional material is published online only. To view please visit the journal online.

Cite this as: Islam MS and Firoz M. MXene Materials for Biomedical Applications. Premier Journal of Science 2025;11:100090

DOI: https://doi.org/10.70389/PJS.100090

Received: 7 May 2025
Revised: 11 July 2025
Accepted: 11 July 2025
Published: 26 July 2025

Ethical approval: N/a
Consent: N/a
Funding: No industry funding
Conflicts of interest: N/a
Author contribution: Md. Saiful Islam: Conceptualization, formal analysis, and writing – original draft. Mubashwera Firoz: Revision and revise based on the reviewer suggestion
Guarantor: Md. Saiful Islam
Provenance and peer-review: Unsolicited and externally peer-reviewed
Data availability statement: N/a

ABSTRACT

MXenes, as a new kind of two-dimensional transition metal carbides, nitrides, and carbonitrides, have attracted enormous attention owing to their distinctive physicochemical performance and extensive biomedical applications. Due to their high electrical conductivity, good mechanical properties, high specific surface area, and hydrophilicity, they are very attractive for several biomedical applications. This review provides a comprehensive overview of the synthesis strategies and intrinsic properties of MXenes, along with their recent advancements in biomedical applications, such as drug delivery, biosensing, cancer therapy, and tissue engineering. Additionally, it discusses the current limitations and explores potential directions for the future development of MXene-based materials in the biomedical field. Functionalized MXenes show promise in targeted drug delivery systems with a controlled release effect for better therapeutic performance, according to recent reports. Furthermore, MXene-based biosensors are helpful in diagnostics because they are sensitive and selective in the identification of biomolecules. Their use in cancer treatment, including localized tumor ablation, is further guaranteed by their photothermal conversion efficiency. Furthermore, the potential for nanoscale MXene modification opens the door for scaffold design and construction in regenerative medicine. However, stability under physiological conditions, long-term biocompatibility, and high yield production remain crucial concerns. This review addresses important issues, outlines future research directions to fully realize the clinical potential of MXene materials, and highlights recent advancements in their development and application in biomedicine.

Keywords: MXenes, Biomedical applications, Drug delivery, Photothermal therapy, Biosensing

Introduction

MXenes are a unique class of two-dimensional (2D) materials first reported in 2011, thanks to the work of Professors Yury Gogotsi and Michel W. Barsoum at Drexel University.[1] Recent studies in 2025 have demonstrated advancements in MXene-based platforms for biosensing, drug delivery, and tissue engineering, highlighting their multifunctional role in next-generation medical technologies.[2,3] The emergence of surface-modified MXenes has particularly improved biocompatibility and targeted therapeutic performance, opening new avenues in clinical translation.[4]

The popularity of MXene materials stems from their diverse and advantageous physicochemical properties and potential uses. These include good electrical and optical behavior, semiconducting features, thermal stability, hydrophilicity (which means they have an affinity for water), magnetic properties, and various surface terminations. Usually, MXenes are made from a class of compounds called MAX phases, which have the general formula $M_{n+1}X_nT_x$. In $M_{n+1}X_nT_x$, M stands for a transition metal, X is carbon and/or nitrogen, T represents different surface terminations such as -O, -F, or -OH, and n can be between 1 and 3. The very first MXene created was $Ti_3C_2T_x$. It was made by selectively etching away aluminum from a compound called Ti_3AlC_2, a process first introduced in the research community.[5,6]

These materials, along with their derivatives, show an impressive combination of qualities, such as high electrical conductivity, excellent mechanical strength, optical features, water-loving nature, and chemical stability. Because of these features, MXenes are considered promising candidates for a wide variety of uses, such as cleaning up the environment, filtering water, storing energy, making stronger composite materials, and even in biomedical applications as drug and gene delivery or pharmaceuticals.[7–12] Additionally, MXenes have been explored for biosensing, antibacterial applications, bioimaging (including magnetic resonance and photoacoustic imaging), and theranostic nanomedicine, particularly in cancer diagnosis and therapy.[6,13–17] Their tunable optical and magnetic properties enhance their utility in these areas. Moreover, their strong pollutant adsorption capacity and antimicrobial effects make them effective for environmental cleanup and antibacterial treatments.[18–20]

Dutta et al. provided a comprehensive review on MXenes and MXene-based composites, covering their synthesis methods, physicochemical properties, and diverse biomedical applications, including drug delivery, biosensing, and tissue engineering.[20]

Biomedical applications of MXene and MXene-based materials are shown in Figure 1.

With the rapid advancement of biomedicine, 2D materials such as boron nitride (hexagonal), graphene, layered double hydroxides, transition metal oxides, and MXenes have gained attention for their potential in biomedical applications. Among these, MXenes stand out due to their surface rich in functional groups, tunable composition, complete metal atomic layers, and excellent hydrophilicity. These features make them highly adaptable and promising for various medical uses. MXenes are promising in the biomedical field because they can be made in large quantities at a low cost. This enhances their practical utility in medical applications.

Currently, they are being explored for applications such as imaging, fighting bacteria, sensing, delivering drugs, and supporting tissue growth, along with other

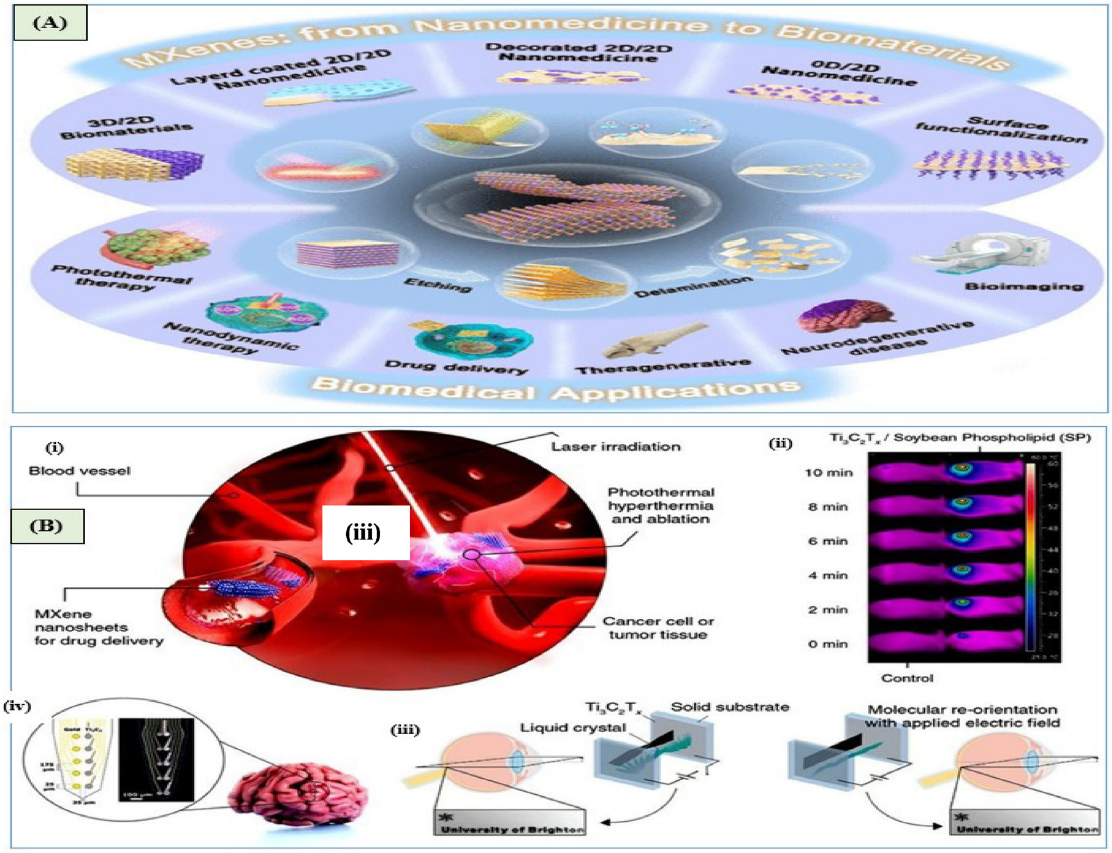

Fig 1 | (A) Various biomedical applications of MXene.[20] (B) Conceptual diagram showcasing diverse biomedical applications of MXene-based materials (i), infrared thermal visualization of a 4T1 tumor-bearing mouse, illustrating temperature changes pre- and postintravenous injection of $Ti_3C_2T_x$-SP (20 mg/kg) under 808 nm laser exposure (1.5 W/cm²) at different time intervals, confirming a strong photothermal effect (ii),[21] schematic representation of a neural interface system employing MXene electrodes for brain activity monitoring (iii),[22] and illustration of a variable-focus lens structure, featuring $Ti_3C_2T_x$-coated glass substrates sandwiching a twisted-nematic liquid crystal layer (iv)[23]

treatment methods. For example, their ability to absorb near-infrared (NIR) light is useful for photothermal therapy (PTT), which can specifically target and destroy cancer cells while sparing healthy tissue nearby. MXenes can also be contrast agents that help doctors track tumors in real time, and they can carry cancer-fighting drugs directly to the trouble spots. The integration of PTT, chemotherapy, and real-time imaging has substantially enhanced cancer treatment outcomes. Furthermore, MXenes are showing potential in making safe sensors for quick biological tests. To unlock further biomedical applications, scientists focus on modifying their surfaces, since this makes MXenes more versatile. Although MXene research remains in its nascent stages, the fact that their surfaces can be easily tuned opens up many exciting possibilities for new functions and innovative applications in medicine.

Even though there's a growing amount of research on MXene materials, a clear and up-to-date summary of their medical applications remains limited.[1–8,24] This review aims to systematically analyze the recent developments in MXene technologies used in various biomedical domains, including drug delivery, biosensing, tissue engineering, and PTT. We point out new trends, discuss the challenges faced so far, and suggest directions for future research. Our goal is to connect the basics of how these materials work with real-world medical applications, providing a fresh perspective for researchers interested in using MXene to create new biomedical solutions.

Methods of Synthesis

The synthesis of MXene materials typically relies on two primary strategies: top-down and bottom-up synthesis, both of which enable the production of single-layer or multilayer MXene structures.[25]

Top-Down Synthesis Method

In this approach, MXenes are synthesized by exfoliating bulk MAX phase crystals using chemical etching and mechanical forces. Typically, hydrofluoric acid (HF) is used to selectively etch the Al layers from MAX phases such as Ti_3AlC_2, followed by delamination using sonication and intercalation agents (e.g., DMF, DMSO, TBAOH) to produce ultrathin 2D flakes.[26] Inorganic intercalants such as metal hydroxides and halide salts are also used for larger MXenes.[27] Figure 2 shows the element composition of MAX phases and MXenes (I), MXene synthesis from MAX phases (a), and an overview of their structure, benefits, challenges, and advances (b).

 DOI: https://doi.org/10.70389/PJS.100090 | Premier Journal of Science 2025;11:100090

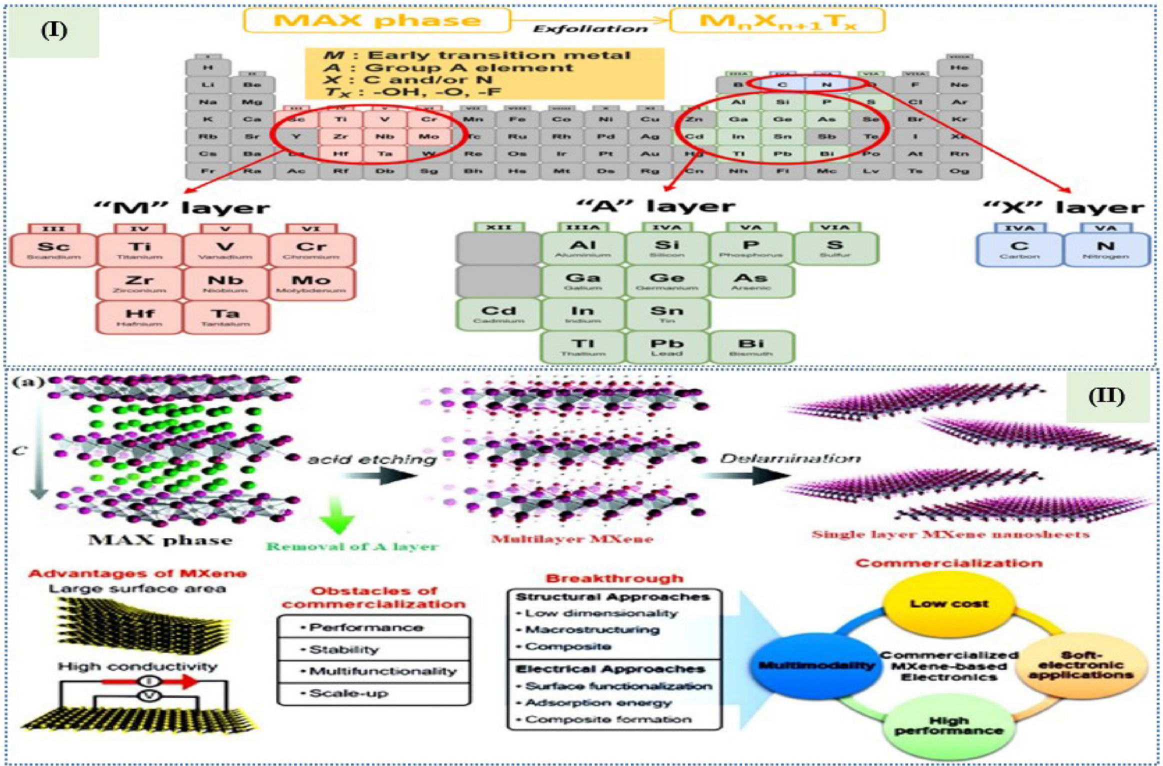

Fig 2 | (I) General formula of MAX phase and MXene and their elemental composition.[28] (II) MXene synthesis using MAX phase compounds (A), and MXene scheme, advantages, limitations, and breakthrough (B)[29]

Due to the toxicity of HF and its fluorine-rich surface products, alternative fluoride-free etching methods have been developed. Naguib et al. prepared Ti_3C_2 from Ti_3AlC_2 using HF at room temperature, while Ghidiu et al. explored molten fluoride etching at elevated temperatures.[30] Other strategies include using TMAOH[31] anodic corrosion with NH_4OH,[32] thermal-assisted HCl etching,[33] and chemical scissor-mediated topotactic transformations.[34] These methods enhance safety, yield, and MXene properties for applications such as catalysis and biomedicine.

Bottom-up Synthesis Method

This approach is preferred when direct exfoliation is challenging, offering control over morphology, composition, and surface functionality. It uses inorganic precursors to grow MXene structures via chemical vapor deposition (CVD) or wet chemical synthesis. Chuan Xu et al.[35] demonstrated CVD synthesis of ultrathin Mo_2C using methane and Cu-impregnated Mo foil, forming Mo-Cu alloys at high temperatures (>1085°C), followed by carbon incorporation. Rapid cooling yielded nanometer-thick crystals with ~100 µm lateral size. More recently, MXenes have been synthesized directly from metals and halides via CVD, bypassing etching steps.[36] These methods produced unique spherulite-like MXene sheets with enhanced surface exposure, showing excellent lithium-ion storage capabilities. Bottom-up techniques offer scalable and tunable routes for advanced MXene applications.

Lewis acidic etching has recently gained significant attention as an emerging strategy for MXene preparation due to its numerous advantages. This method is primarily characterized by its etching mechanism, ability to control surface terminations, formation of in situ metals, and efficient delamination of multilayered MXenes (Table 1).

Biomedical Applications of MXenes

MXene materials, known for their biocompatibility, photothermal properties, and conductivity, are utilized in various biomedical applications, including cancer theranostics, drug delivery, biosensing, tissue engineering, and implantable devices. Their high surface area, functionalization capacity, and electro-optical characteristics make them ideal for next-generation diagnostic and therapeutic technologies. MXene materials have emerged as promising candidates for cancer theranostics due to their biocompatibility, low cytotoxicity, and excellent photothermal conversion efficiency across the NIR and IR ranges as seen in Figure 1A.[46] Notable examples include $Ti_3C_2T_x$, Nb_2CT_x, and $Ta_4C_3T_x$, with $Ta_4C_3T_x$ showing superior photothermal efficiency (44.7%) compared to $Ti_3C_2T_x$.[47]

In vitro and in vivo studies demonstrated that over 90% of breast cancer cells were effectively destroyed using NIR-irradiated, soybean phospholipid-modified $Ta_4C_3T_x$ (Figure 1B(ii)). Beyond cancer therapy, MXenes have applications in MRI-guided tumor heating and drug delivery.[48] $Ti_3C_2T_x$-based implantable brain

Table 1 | Summary of MXene properties and their diverse applications

Types of MXene and Their Composites	Essential Features	Precise Biomedical Uses	References
Ti_3C_3	It exhibits high electrical conductivity, excellent hydrophilicity, remarkable flexibility, and outstanding photothermal capabilities.	Biomedical devices, PTT, neural tissue regeneration, and antibacterial functions.	37
Nb_2C	The material shows potential for tumor ablation, osteoconductivity, and antibacterial activity.	Promotes bone healing and suppresses tumor development.	38
Ta_4C_3	The material offers enhanced electrical properties and good biocompatibility.	Applicable in bioelectronic devices and high-performance supercapacitors.	39
Ta_4C_3/IONP/SP	This MXene composite provides enhanced multimodal imaging capabilities and maintains stability in physiological settings.	Applicable in combined cancer diagnosis and treatment strategies.	40
Ti_3C_2-PEG	The material demonstrates biocompatibility and promotes synchronized cardiomyocyte beating and gene expression.	Applicable in cardiac patches for heart tissue regeneration postinfarction.	41
Ti_3C_2-Chitosan	The material offers enhanced biocompatibility, biodegradability, structural stability, and antibacterial properties.	Enhances cell delivery, enables wearable biosensing, and supports tissue engineering applications.	42
Ti_2C_2-Gold Nanoparticle	It exhibits excellent biocompatibility, efficient biodegradability, robust structural stability, and strong antibacterial effects.	Used for the detection of cardiac biomarkers in diagnostic applications.	43
Ti_3C_2-PCL	The material shows increased hydrophilicity and conductivity, along with enhanced protein adsorption and cell attachment.	For tissue engineering of cardiac and bone tissues.	44
Ti_3C_2-PANI	Enhanced electro-conductivity and interlayer spacing improve material performance.	Used in bioelectronics and biosensing technologies.	45

electrodes outperform gold microelectrodes in in vivo neuronal recording and impedance (Figure 1B(iii))).[15] MXene electrode arrays also exhibit high-resolution surface electromyography performance without requiring gels.[49] $Ti_3C_2T_x$'s electro-optical features support its use in adjustable-focus intraocular lenses mimicking the eye's natural lens (Figure 1B(iv)).[23] Additionally, $Ti_3C_2T_x$ and $Mo_2TiC_2T_x$ MXenes demonstrate high efficiency in urea and uric acid adsorption from dialysate, potentially enabling wearable artificial kidneys.[50] This is attributed to the small, charged, and functionalized gaps on 2D MXene, which act as effective adsorption sites. Some specific biomedical applications of MXenes and their various composite materials are described below.

Wound Healing

Wound healing is a complex and dynamic biological process involving inflammation, tissue regeneration, and remodeling to restore skin integrity after injury. The largest organ in the body, the skin protects the body from a variety of external dangers, including heat, UV rays, infections, and physical harm. Damage to the skin can lead to serious complications, including wound infections that negatively affect overall health.[51,52] Skin wound healing involves four stages: hemostasis, inflammation, proliferation, and tissue remodeling, requiring coordination among various cell types.[53] An ideal wound dressing should maintain optimal temperature, support cell proliferation and migration, and possess antimicrobial properties.[54–56] Hydrogel-based dressings are promising for this purpose due to their ability to maintain a moist environment, mimic the biological microenvironment, and allow oxygen permeability. However, their uncontrolled behavior during healing limits their efficacy.[57]

To enhance healing outcomes, Yang et al. developed a hydrogel composed of regenerated bacterial cellulose and MXene nanosheets, activated by external electrical stimulation.[58] As shown in Figure 3A, the composite hydrogel was synthesized via covalent cross-linking and hydrogen bonding. Fluorescence imaging demonstrated enhanced NIH3T3 cell activity and density under electrical stimulation (Figure 3B). In vivo rat experiments confirmed improved tissue regeneration with electric field application (0–400 mV), where treated wounds showed faster closure and reepithelialization (Figure 3C). Histological analyses (Figure 3D) further revealed enhanced angiogenesis, reduced inflammation, and superior healing compared to commercial dressings.

Finally, MXene materials have the ability to generate reactive oxygen species and damage bacterial cell membranes, which allows them to demonstrate broad-spectrum antibacterial action. This helps to avoid infection at the location of the wound or injury. Within the wound region, it has the ability to stimulate tissue regeneration through the use of electrical signals. Furthermore, this material has the potential to act as nanocarriers for controlled medication release, which would allow for the targeted administration of anti-inflammatory or regenerative medicines directly to the location of the wound for treatment. MXene-based materials are also considered potential candidates for biosensing and diagnostics.

Biosensing and Diagnostics

MXene-based materials have gained considerable attention in sensor development due to their tunable surface chemistry, redox activity, and excellent electrocatalytic properties, making them suitable for detecting

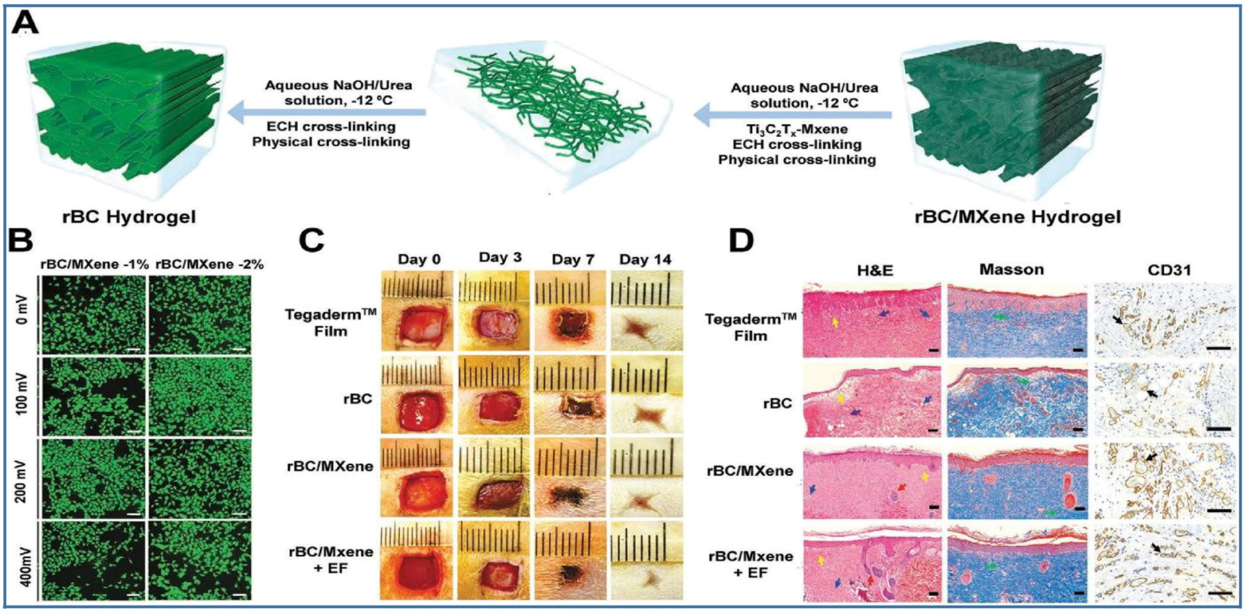

Fig 3 | (A) Illustration showing the formation pathway of cellulose (rBC)-based hydrogels. (B) Confocal imaging showing Live/Dead staining results. (C) Comparison of wound healing progression for 0–14 days. (D) Histological evaluation of tissue regeneration for CD31^{+} microvessels[57,58]

biomarkers, drugs, nanoparticles, and environmental toxins.[59,60] Their applications encompass various sensor types, such as strain sensors, and optical, gas, humidity, and electrochemical sensors. $Ti_3C_2T_x$ MXene exhibits broad optical absorption (visible to NIR) and strong photothermal effects, which enhance gas molecule detection via adsorption-induced resistance changes. Additionally, pristine $Ti_3C_2T_x$ has been used as a chronoamperometric biosensor for glucose, offering high sensitivity and wide linear detection ranges.[61]

Despite their advantages, MXenes tend to aggregate due to van der Waals forces, reducing surface area and limiting ion transport. This issue can be mitigated by fabricating composites with increased interlayer spacing to boost efficiency.[62–65] Their integration into personal diagnostic tools, such as biosensors for glucose or disease monitoring, shows promise for decentralized healthcare.[27,66] MXene composites with fluorescent dyes, such as rhodamine B, have also been explored for optical sensing. The quenching and restoration of fluorescence in response to phospholipase D activity offers a novel route for biosensing.[67] Their unique physicochemical properties support the development of advanced biosensors for clinical use.[68,69]

Recent advancements have highlighted MXenes in flexible electronics and biosensors due to their conductivity, large surface area, and catalytic properties. MXene-based self-powered e-skin sensors demonstrated temperature monitoring capabilities.[70] Their composites enable electrochemical biosensing with high sensitivity and fast response, such as $Ti_3C_2T_x$–Chitosan GCE for sarcosine detection[71] and Au/MXene nanocomposites for enhanced glucose sensing.[72] MXenes also amplify signals in cancer biomarker detection via DNA-ferrocene probes.[73] For exosome detection, aptamer-MXene nanoprobes used FRET-based fluorescence recovery (Figure 4B). MXene–NiFe hybrids acted as nanocatalysts for colorimetric glutathione detection via H_2O_2 decomposition and TMB oxidation (Figure 4C).

MXene-based colorimetric sensors utilize TMB oxidation for visual detection, fading upon glutathione presence (Figure 4C). Additionally, MXene–DNA composites, using Ti–phosphate chelation, enabled sensitive gliotoxin detection via tetrahedral DNA structures, enhancing electron transfer and producing electrochemical signals proportional to gliotoxin concentration (Figures 4A, B).[75] MXene-based composites have addressed limitations in wearable electrochemical biosensors, improving enzyme stability, detection range, and durability. For example, a MXene–Prussian blue composite enabled reliable glucose and lactate detection in sweat using a hydrophobic carbon fiber-based interface, showing high sensitivity and repeatability (Figures 4C).[76]

In oral health monitoring, a flexible 3D cellulose/$Ti_3C_2T_x$ MXene bioaerogel sensor detected pressure and ammonia, aiding periodontal disease diagnosis (Figure 5). Additionally, dip-coated $Ti_3C_2T_x$ nanosheets on cellulose fabric created breathable, conductive smart textiles (M-fabrics) for breath monitoring, thermotherapy, and antibacterial wound care, highlighting MXenes' potential in multifunctional wearable healthcare devices.[77]

In summary, MXene-based materials are well-suited for biosensing and diagnosis because they conduct electricity well, have a large surface area, and have useful surface groups. These features enable sensitive and quick biological target detection via signal amplification. MXenes can also support electrochemical and optical sensors for accurate, point-of-care diagnostics. MXene materials' high surface area, variable interlayer

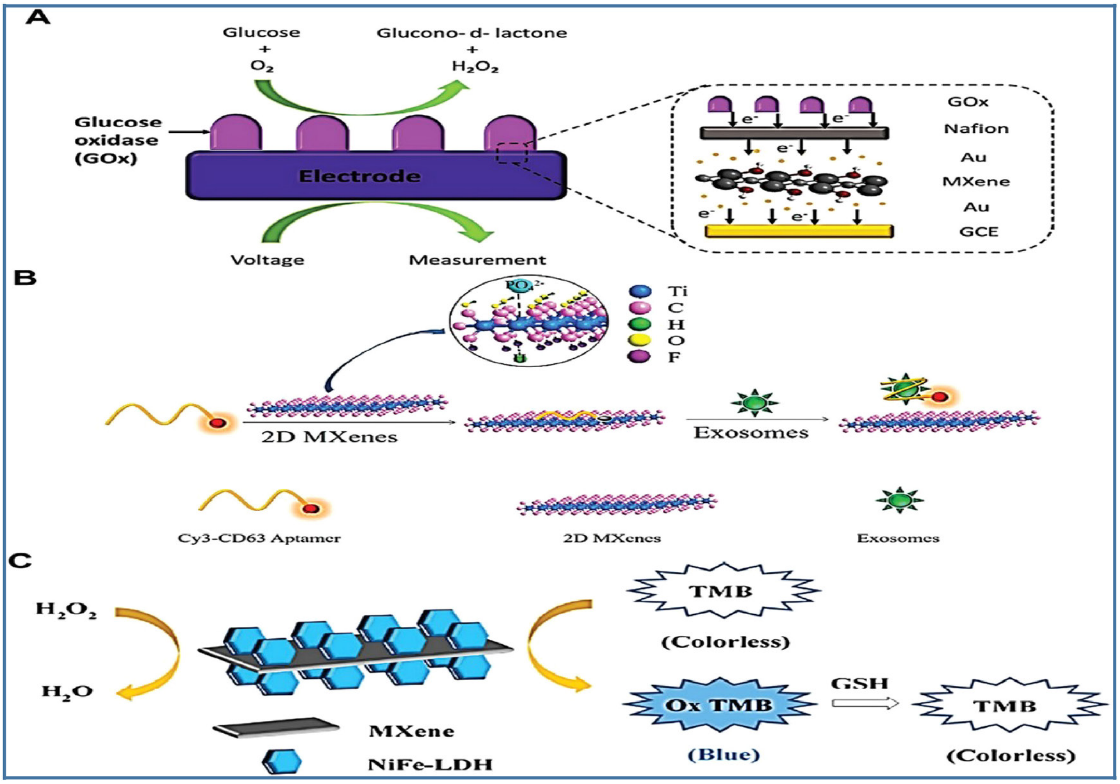

Fig 4 | (A) Schematic representation of an enzyme-based biosensor used for glucose detection. (B) Visual depiction of exosome biomarker detection: Cy3-CD63 aptamer combined with MXene nanosheets in a quenched fluorescence state, where fluorescence is restored upon exosome interaction.[74] (C) Illustration of a composite material comprising MXene nanosheets and NiFe layered double hydroxide, designed for glutathione sensing

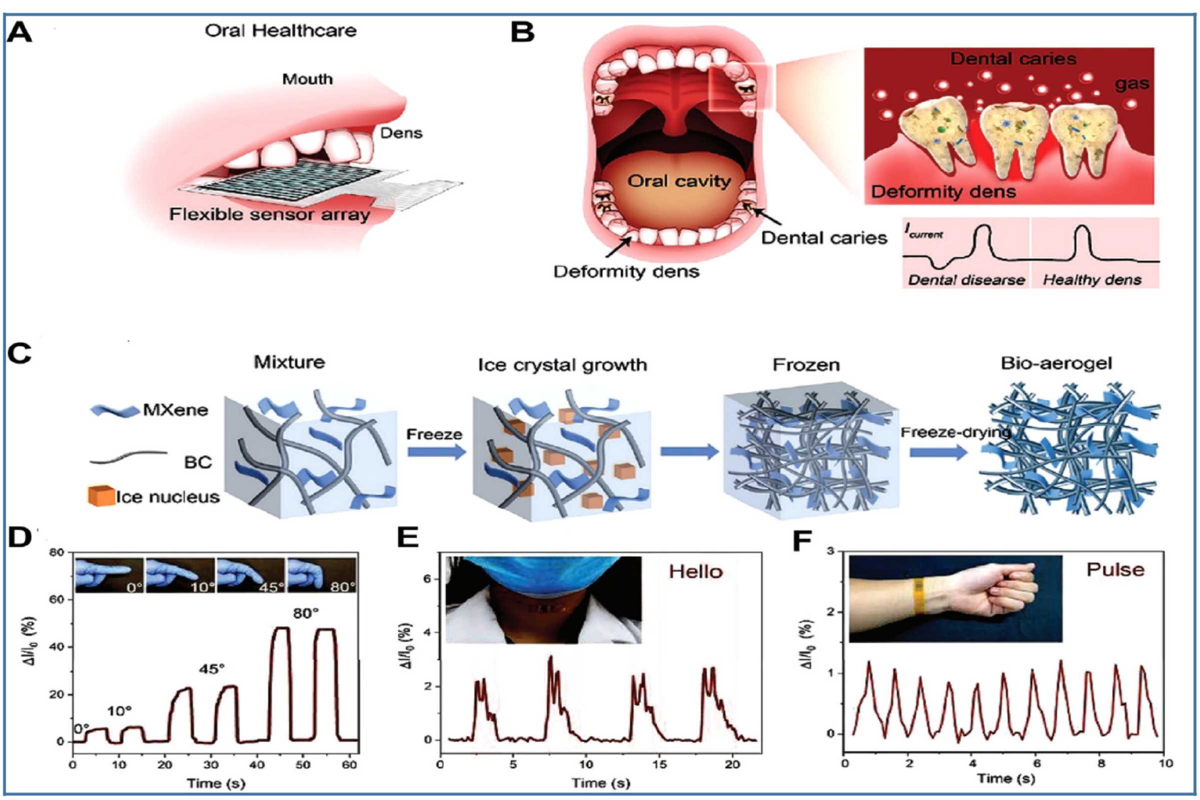

Fig 5 | BC/MXene bioaerogel-based soft sensing device. (A and B) Design concept and operational mechanism of a BC/MXene bioaerogel-based flexible sensor, (C) Schematic representation of the BC/MXene bioaerogel preparation process. (D) Variation in pressure-sensing signals corresponding to different index finger bending angles. (E and F) Application of the sensor in sound detection by tracking vocal cord vibrations when attached to the throat, and in health monitoring by capturing wrist pulse signals. The average resting pulse rate was measured at 70 beats/min[78]

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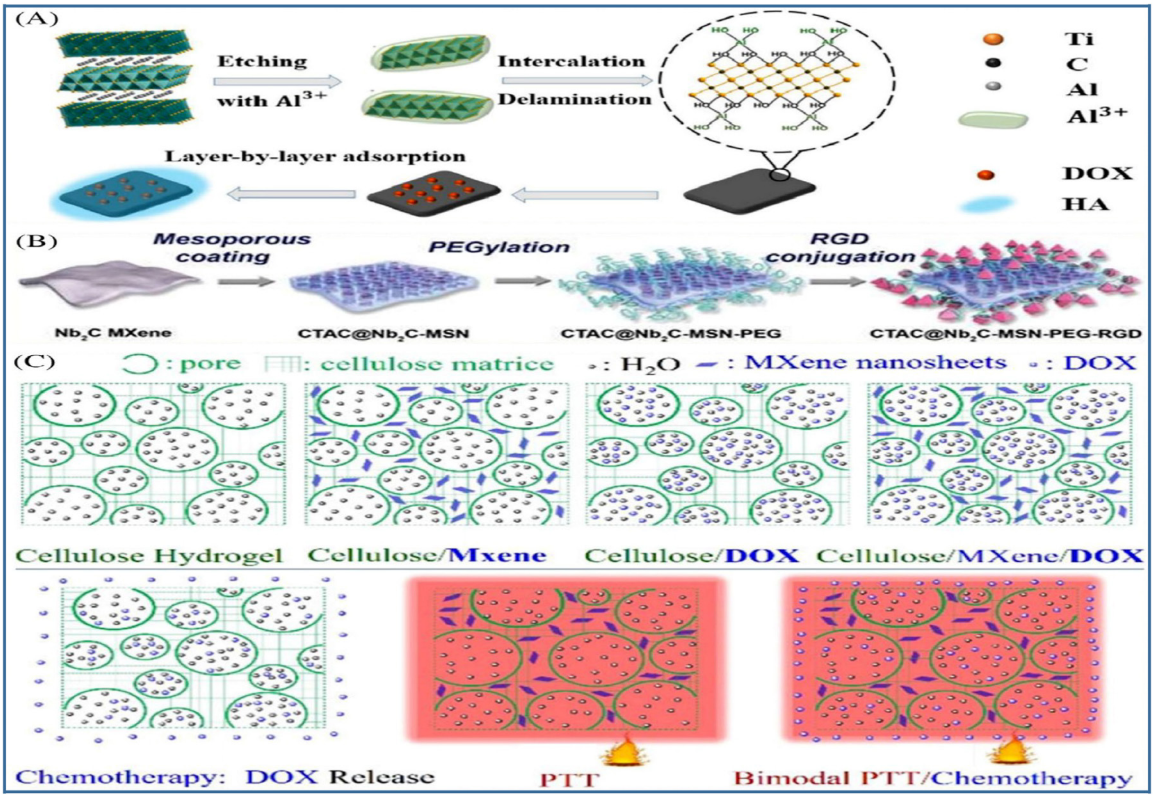

Fig 6 | MXene-based platforms for drug delivery applications. (A) Illustration of the stepwise assembly process used to create a Ti_3C_2 nanoplatform via layer-by-layer adsorption.[79] (B) Schematic representation of the preparation and chemistry of surface engineering of CTAC@Nb_2C-MSN through sol-gel chemistry.[80] (C) Overview of four types of cellulose-MXene composite hydrogels and their drug release behavior under various conditions[81]

spacing, and surface functionalization potential make them promising for medication delivery, controlled release systems, and diagnostics.

Drug Delivery and Controlled Release

MXene-based nanomaterials have emerged as highly efficient platforms for targeted cancer drug delivery due to their unique 2D structure, large surface area, and excellent biocompatibility. Ti_3C_2 MXene, with its negatively charged surface, can strongly adsorb cationic anticancer drugs such as doxorubicin (DOX), achieving a high drug loading capacity of up to 84.2%. Liu et al. demonstrated that a Ti_3C_2-DOX system responds to multiple stimuli, including pH, enzymes, and NIR light, enabling controlled and on-demand drug release (Figure 6A).[79] To address limitations in surface functionality, Han et al. developed Nb_2C MXene-based nanocarriers with mesoporous silica coatings via sol-gel chemistry. These carriers showed a drug loading of 32.57% and targeted delivery via RGD peptide conjugation, along with strong photothermal effects (Figure 6B).[80] Furthermore, Xing et al. introduced a composite hydrogel of cellulose and Ti_3C_2 MXene that enabled rapid DOX release upon 808 nm NIR irradiation, enhancing therapeutic efficiency (Figure 6C).[81]

Antibacterial Activities of MXene

MXenes exhibit notable antibacterial properties due to their semiconductor characteristics, excellent electrical conductivity, hydrophilicity, atomic-layer thickness, and oxygen-containing functional groups. Kashif et al. demonstrated that $Ti_3C_2T_x$ in aqueous solution effectively inhibited both Gram-negative *Escherichia coli* and Gram-positive *Bacillus subtilis*, surpassing the antibacterial activity of graphene oxide (GO), with effectiveness depending on dose.[82] The primary mechanism involves direct interaction between $Ti_3C_2T_x$ nanosheets and bacterial membranes, leading to structural disruption and cell death. Their small size and reactive surface facilitate penetration into microbial cells, enhancing bactericidal effects. Additionally, negatively charged Ti_3C_2 nanosheets create conductive bridges on lipid bilayers, promoting electron transfer that disrupts cellular function. Hydrogen bonding with lipopolysaccharide chains may also inhibit bacterial growth.

Ahmad Arabi et al. found that antibacterial activity was size- and exposure time-dependent, with smaller nanosheets showing higher efficacy due to physical membrane disruption (Figure 7A).[75] Rajavel et al. identified ROS generation as another mechanism, showing that MXenes reduce antioxidant enzyme (SOD) activity, leading to oxidative damage.[83] Feng et al. developed a Ag@Ti_3C_2@Cu_2O nanocomposite via a wet chemical method, showing potent photocatalytic antibacterial activity and enhanced charge separation, extending electron lifetime and improving bacterial killing against *Pseudomonas aeruginosa* and *Staphylococcus aureus* (Figure 7B).[84]

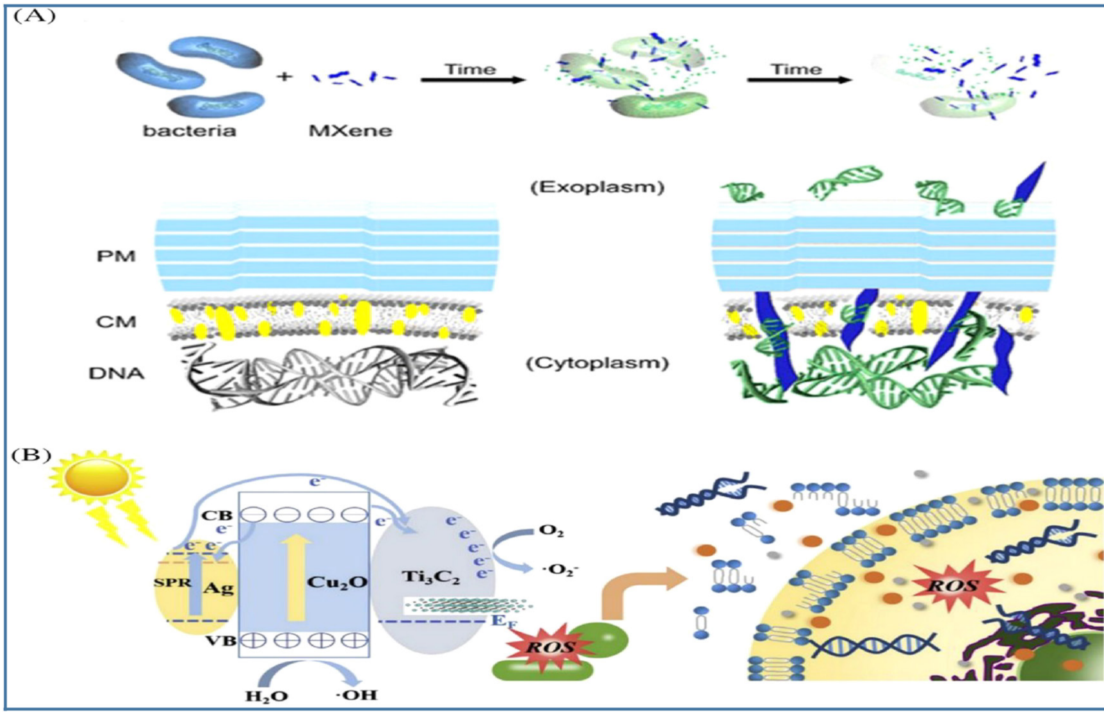

Fig 7 | Antibacterial mechanisms of MXenes. (A) Diagram depicting the suggested mode of action (MoA) of $Ti_3C_2T_x$ nanosheets, showing interaction with bacterial structures, including the peptidoglycan mesh (PM) and cytoplasmic membrane (CM).[75] (B) Illustration of the structural configuration, energy band alignment, electron-hole separation process, and antibacterial action of the Ag@Ti_3C_2@Cu_2O nanocomposite[84]

Finally, it can be said that the MXene-based materials are very effective at killing a wide range of bacteria by breaking their membranes and producing reactive oxygen species, and they are less likely to lead to resistance than regular antibiotics. Their surfaces can be functionalized to enhance both antimicrobial efficiency and biocompatibility. These properties make them highly suitable for applications in tissue engineering and regenerative medicine, where infection control and cell support are crucial.

MXenes for Tissue Engineering and Regenerative Medicine

MXenes, particularly Ti_3C_2 and $Ti_3C_2T_x$, have emerged as multifunctional materials for tissue engineering and regenerative medicine due to their exceptional physicochemical and biological properties. Ti_3C_2 MXene nanofibers, fabricated via electrospinning, exhibited hydrophilic surfaces rich in functional groups conducive to cellular growth and osteogenic differentiation of BMSCs.[85] Ti_3C_2 MXene quantum dots (QDs) promoted immunomodulation and enhanced tissue repair by reducing $CD4^+IFN\text{-}y^+$ T-cell activation and expanding regulatory T-cells.[86] Incorporating Ti_3C_2 QDs into chitosan hydrogels yielded conductive, injectable, and thermosensitive platforms for stem cell delivery.[86] Similarly, $Ti_3C_2T_x$-reinforced PLA membranes enhanced the tensile strength and osteogenic response of MC3T3-E1 cells.[87,88] For cancer therapy and bone regeneration, Ti_3C_2-integrated 3D-printed bioactive glass scaffolds enabled photothermal tumor ablation and bone regrowth (Figure 8).[89] MXene-based conductive hydrogels have shown promising potential in promoting neural and cardiac tissue regeneration, while MXene composites also enhance osteogenic differentiation, supporting bone regeneration.

Advanced MXene-based bioinks for 3D bioprinting demonstrated superior printability, electrical conductivity, and >95% cell viability.[90] $Ti_3C_2T_x$ QDs exhibited stable subcellular localization and autofluorescence for nanomedicine tracking.[91] rGO-MXene hydrogels supported cell adhesion, migration, and nutrient diffusion across multiple human cell types.[92] Composite membranes combining Ti_3C_2 and hydroxyapatite improved mechanical strength and bone regeneration in vivo.[42] An electroconductive Ti_3C_2-MXene-Chitosan-honey composite showed biocompatibility and potential for tissue applications.[50] $Ti_3C_2T_x$ also demonstrated selective urea adsorption for dialysis systems,[44] while polycaprolactone–MXene fibers supported preosteoblast proliferation.[58] Lastly, bacterial cellulose–$Ti_3C_2T_x$ hydrogels enhanced wound healing under electrical stimulation, outperforming commercial dressings.[93]

A multifunctional biomaterial was developed by integrating 2D Nb_2C MXene, grafted with S-nitrosothiol-functionalized mesoporous silica, into 3D-printed bioactive glass scaffolds for synergistic osteosarcoma therapy and bone regeneration.[14] The system enabled NIR-II-triggered PTT and on-demand nitric oxide release to support vascularization and bone repair. Nb_2C MXene exhibited high photothermal conversion efficiency (36.4% NIR-I, 45.65% NIR-II), biodegradability, and biocompatibility.[94] Additionally, Nb_2C-based microneedle systems with

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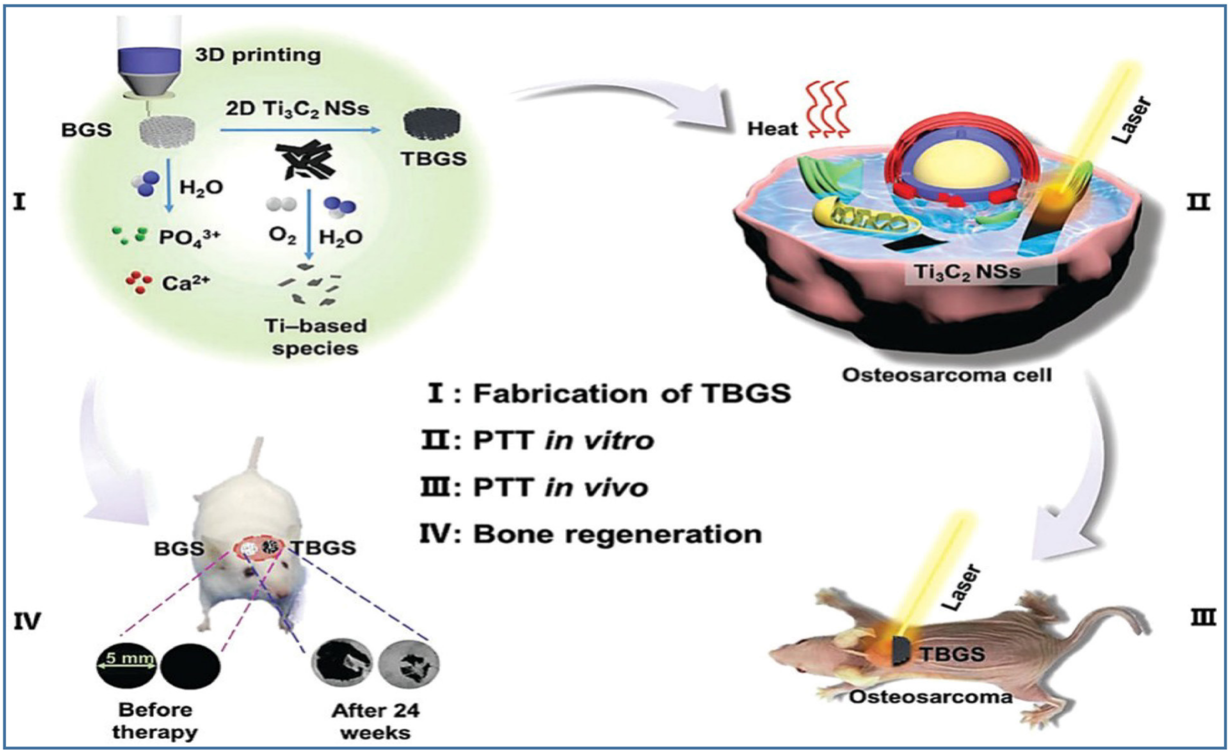

Fig 8 | (I) The preparation process of Ti_3C_2-bioactive glass (BG) scaffold (TBGS). (II and III) Bone cancer treatment, both in vitro and in vivo and (IV) Bone tissue regeneration

Table 2 | MXene-integrated nanocomposites for regenerative medicine

Types of MXene Composites	Tissue-Directed Therapy	Important Applications	References
MXene-PVA nanofibers encapsulating amoxicillin	Skin	This membrane serves as a drug carrier and physical barrier, offering strong antibacterial effects and promoting faster wound healing.	96
Bioglass-integrated with NbSiR	Bone and PTT-IT	The BG@NbSiR scaffold eradicates primary tumors, enhances immune response, prevents metastasis, supports bone regeneration, and acts as a tumor vaccine by providing diverse antigens after PTT.	97
Muscle-inspired MXene/PVA hydrogel	Skin and PTT	The MXene-based hydrogel offers strong, broad-spectrum antibacterial activity via photothermal hyperthermia, resists drug resistance, and features excellent mechanical properties for infected site treatment.	98
Nanosheets of $Ti_3C_2T_x$	Skin	The multifunctional composite effectively heals MRSA-infected wounds by reducing inflammation, boosting cell growth, and promoting tissue regeneration and angiogenesis.	99
Chitosan–hyaluronate hydrogel@ $Ti_3C_2T_x$ nanocomposites	Skin	It showed effective antibacterial activity against *E. coli*, *S. aureus*, and *Bacillus* species.	100
Nb_2C MXene-enhanced 3D-printed bone-analogous structure	Bone and PTT	Niobium carbide MXene promotes blood vessel formation and migration, enhancing oxygen and nutrient delivery to support bone repair.	92
TiC-based nanocomposite embedded with ultralong hydroxyapatite nanowires	Bone	The material showed better mechanical strength and hydrophilicity, boosting cell adhesion, growth, and bone regeneration in rat skull defects.	101
MXene/hydroxyapatite nanoparticle composite nanofibers	Bone and PTT	MXene/hydroxyapatite nanofibers combined photothermal and osteogenic effects, showing biocompatibility and promoting bone stem cell growth and differentiation.	93
Silica@Nb_2C-integrated 3D-printing bioactive glass scaffolds	Bone	The composite's controllable NO release, strong photothermal effect, and bone regeneration support make it a promising platform for multifaceted bone tumor treatment.	102
Nb_2C titanium plate (Nb_2C@ TP)-based implant	Skin	The Nb_2C@TP implant reduces inflammation by scavenging reactive oxygen species and promotes angiogenesis and tissue repair.	46

polyvinylpyrrolidone provided minimally invasive, dissolvable platforms for localized NIR-II photothermal tumor therapy with high biocompatibility and effective skin penetration (Table 2).[95]

Finally, MXene-based materials show great promise in tissue engineering and regenerative medicine because they are very compatible with living tissues, conduct electricity well, and help cells stick, grow, and develop properly. They may also be integrated into scaffolds to facilitate tissue repair and regeneration, simultaneously mitigating the risk of infection. The various useful features of MXenes make them very fitting for advanced medical uses, especially in cancer treatment, where accurate delivery and effective treatment are crucial.

Cancer Therapy

In recent years, MXenes have shown great promise in cancer therapy due to their strong NIR absorption, excellent photothermal conversion efficiency, and biocompatibility. Their application in PTT and photodynamic therapy (PDT) enables precise, localized cancer treatment with minimal damage to healthy tissues. Li et al.[103] demonstrated that Ti_3C_2 MXene exhibits superior light-to-heat conversion compared to carbon nanotubes, achieving nearly 100% efficiency and strong absorption around 800 nm. However, instability in saline and aggregation prompted structural modifications. Gao et al.[104] addressed this by designing a stable 3D Ti_3C_2/CNT honeycomb architecture.

MXenes are also effective in PDT, where photosensitizers activate under light, minimizing side effects.[79] Liu et al.[26] confirmed MXene's efficient drug release under NIR and acidic conditions. Various MXene composites, such as Ti_3C_2 QDs[105] Ti_2C nanosheets[106] and MXene/Doxjade platforms,[107] have further enhanced cancer therapy. Ding et al.[40] created $Ti_3C_2T_x$-coated PLA electrospun fibers with unidirectional thermal conductivity, reaching 70°C in 1 min. These films effectively killed cancer cells and reduced tumor recurrence. Their antimicrobial activity under 808 nm NIR light was also notable, attributed to the enhanced thermal response of MXene-loaded fibrous structures. Figure 9 shows a multifunctional nanocomposite composed of Ta_4C_3, iron oxide nanoparticles (IONPs), and soybean phospholipids, designed for dual-modal MRI/CT imaging and PTT-guided breast cancer treatment.

Finally, MXene-based materials offer great potential in cancer therapy through their efficient photothermal and photodynamic properties, enabling precise tumor destruction. Their high surface area and functionalization allow for targeted drug delivery with reduced side effects. Additionally, their ability to modulate the tumor microenvironment opens new avenues for synergistic immunotherapy approaches.

Biosafety Concerns of MXene-Based Materials

Although MXene-based materials exhibit significant biological potential, it is essential to solve biosafety deficiencies for successful clinical application. Chronic toxicity is a significant issue, as MXenes may accumulate in organs such as the liver, spleen, and kidneys, potentially eliciting immunological responses, inflammation, or cytotoxicity over time. Equally significant is comprehending the breakdown behavior of MXenes in physiological environments, specifically the characteristics and toxicity of their degradation byproducts, which are inadequately characterized. Moreover,

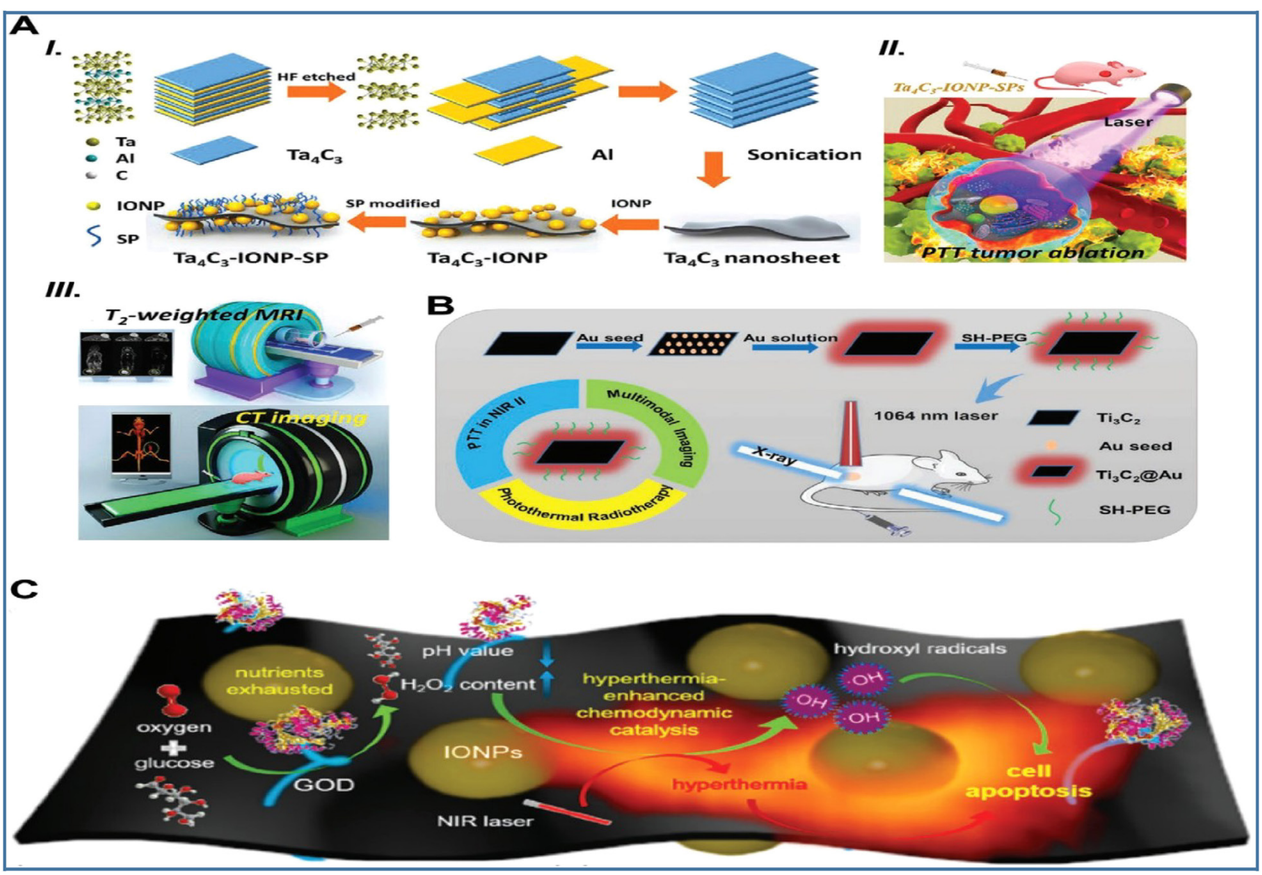

Fig 9 | (A) Illustration of the synthesis process for Ta_4C_3 combined with iron oxide nanoparticles (IONPs) and soybean phospholipids, forming a multifunctional nanocomposite designed for MRI/CT dual-modal imaging and PTT-guided breast cancer treatment.[108] (B) Diagram showing the fabrication of Ti_3C_2@Au nanostructures, subsequent PEGylation, and their use in dual-mode photoacoustic/computed tomography (PA/CT) imaging and PTT-enhanced radiotherapy.[109] (C) Conceptual representation of a therapeutic approach using MXene nanosheets loaded with superparamagnetic IONPs and glucose oxidase (GOD), demonstrating a cascade therapy effect driven by PTT and catalytic activity[109]

regulatory obstacles continue to exist owing to the absence of standardized testing methodologies for 2D nanomaterials. Regulatory agencies such as the FDA and EMA mandate comprehensive pharmacokinetic, toxicological, and biocompatibility data. Consequently, thorough in vivo investigations, prolonged surveillance, and compliance with advancing nanomedicine protocols are crucial for the secure clinical utilization of MXenes.[110, 111]

Concluding Remarks and Future Perspective

MXene materials have emerged as a highly promising class of 2D materials with unique physicochemical properties, including excellent electrical conductivity, high surface area, tunable surface chemistry, and exceptional photothermal conversion efficiency. These characteristics have driven their application in various biomedical fields, such as drug delivery, biosensing, bioimaging, tissue engineering, antimicrobial treatments, and cancer therapy. Their biocompatibility, ease of functionalization, and ability to integrate with other nanomaterials further expand their potential as versatile platforms for next-generation biomedical technologies. Despite significant progress, the clinical translation of MXenes remains in its infancy. Key challenges include understanding their long-term biocompatibility, biodegradability, and in vivo toxicity profiles. One major issue is that there's no standard way to evaluate biosafety. Different studies often use different cell lines, doses, and animal models, which makes it hard to compare results. Also, long-term effects—such as toxicity, how these materials break down in the body, and how they interact with things such as mitochondria and DNA—have not been studied enough.

In vivo studies on healthy and sick models are needed to understand the safety of MXenes, their therapeutic effects, and their potential for targeted treatments, imaging, and combined therapy approaches, requiring collaboration across fields. In particular, MXene nanocomposites that respond to NIR light in the 1000–1700 nm range could enable treatments deep inside tissues and allow precise control of heat for healing and tissue regeneration. Looking ahead, more focus should be placed on exploring how MXenes can be used for biosensing. Their capabilities can be boosted by surface doping or by combining them with metals such as silver (Ag), bismuth (Bi), or gold (Au). This flexibility makes them exciting for new innovations, such as lab-on-a-chip devices, stem cell engineering, and smart biosensors. In order to fully realize their potential, scientists must create cost-effective and scalable methods for producing MXenes as well as dependable surface modification methods. With continued research and increased interest, materials based on MXene have the potential to develop into effective instruments for the advancement of next-generation biomedical technologies.

The diversity in synthetic protocols, terminated surfaces, and the variability from one batch to another force the establishment of guidelines in order to provide reproducibility and safety. Furthermore, encouraging results of the preliminary studies have been shown in preclinical models, but thorough in vivo studies well-designed clinical trials are needed. In the future, interdisciplinary work will be essential to propel MXene research from the laboratory to the clinic. This technique could be incorporated in the development of a new type of multifunctional MXene-based platform, which integrates detection and therapy in a single platform for real-time monitoring and controllable therapy. Likewise, for the process to be green and to be commercially viable at a large scale, we are focusing on green synthesis technology development and scale-up production. As of 2025, MXene materials continue to make substantial strides in biomedical engineering, particularly through the development of fluoride-free, green synthesis methods and sophisticated surface functionalization strategies that improve biocompatibility, stability, and targeted therapeutic performance. Finally, MXenes have great potential in the field of biomedical applications. With more innovation, extensive validation, and transdisciplinary efforts bridging material science, biology, and clinical/medical research, MXenes have the potential to revolutionize the field of precision medicine and a new generation of healthcare technology. We hope that the current review of the literature sets the stage for the next era of exciting discoveries in the ever-evolving discipline of MXene-based biomedicine. Future research should prioritize systematic in vivo studies on long-term toxicity and biodistribution, scalable manufacturing techniques, and integration of AI-guided design to accelerate the translation of MXene-based platforms into clinical healthcare solutions.

Acknowledgments

The authors would like to acknowledge the Bangladesh Army University of Engineering & Technology (BAUET) for providing the required facilities for conducting these research activities.

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