



MXenes: Reshaping Cross-disciplinary Innovation and Application Frontiers in Biomedical Engineering

Wu Wang,^{1,#} Chuang Gong,¹ Jide Zhang,^{1,#,*} Yihuan Kan,¹ Shaochen Zhou,¹ Min Tang,¹ Yabing Gan¹ and Jingfeng Wang^{2,*}

Abstract

MXenes have demonstrated significant advantages in smart diagnostic systems, neural engineering interfaces and tissue regeneration engineering due to their abundant surface functional groups, large specific surface area, metal-like conductivity and excellent photothermal conversion efficiency. However, there are still many key challenges for the deep integration of multifunctional synthesis strategies and biomedical applications, such as the unclear long-term evolution of biocompatibility and immunoregulation mechanisms, and the immature conditions for clinical translation. This review systematically compiles advantages of MXenes, their synthetic pathways, and cutting-edge applications in biomedical engineering, providing researchers with comprehensive technical references. Furthermore, it reveals the translational potential of MXenes in precision tumour therapy, intervention of neurodegenerative diseases, and regenerative medicine, facilitating intelligent and integrated leapfrog development of biomedical engineering.

Keywords: MXenes; Synthesis; Properties; Applications; Biomedical engineering.

Received: 21 April 2025; Revised: 27 May 2025; Accepted: 16 June 2025.

Article type: Review article.

1. Introduction

Since the nanotechnology revolution at the beginning of the 21st Century, the intersection of materials science and life sciences has been searching for novel materials that can push the boundaries of traditional biomedical engineering properties.^[1-3] MXenes were born in this context as a class of two-dimensional (2D) layered materials formed by selective etching of transition metal carbides or nitrides.^[4-6] Their large specific surface area, tunable surface chemistry, excellent metal-level conductivity, and unique interlayer nano-channel structure are perfectly suited for biomedical engineering where multifunctional and integrated materials are required.^[7-9] In areas such as drug delivery systems, neuroengineered interfaces, biosensors and tissue regeneration scaffolds, MXenes promote biomedical technology innovation with their unique physicochemical properties.^[10-12]

The transformation and upgrading of the biomedical engineering industry calls for a leap from single-function

devices to intelligent systems.^[13-15] While traditional materials often only meet a single need, MXenes are able to integrate multiple functions into one through chemical modification and structural design.^[16-18] For example, the rich functional groups on their surface can modify targeted molecules for precise delivery.^[19-21] Their interlayer channels can be loaded with drug molecules for controlled release. And their intrinsic electrical, optical, and thermal response properties allow for external field-controlled activation.^[21-24] This multi-physical field coupled materials design has driven biomedical engineering towards the frontiers of diagnostic and therapeutic integration, organ chips, smart prostheses, and so on.^[25-27] The establishment of an interdisciplinary research network has enabled materials scientists, biologists, engineers and clinicians to collaborate on the mechanisms of MXenes' behaviour in physiological environments, biocompatibility optimisation strategies and clinical translation pathways.^[28-30] The current application of MXenes in the field of biomedical engineering has shown many cutting-edge directions. These include the construction of intelligent diagnostic and treatment integration systems to enhance the effectiveness of tumour treatment through the synergistic effect of photothermal effect and drug release.^[31-33] The development of neural engineering interfaces to improve the quality of neural signal recordings by using the high conductivity and biocompatibility of

¹ College of Biological and Medical Engineering, Hunan University of Technology, No.88 Taishan West Road, Zhuzhou, 412007, China

² Northwest Institute for Nonferrous Metal Research, Xian, 710016, China

These authors contributed to this work equally.

*Email: jdzhang5189@163.com (J. D. Zhang);
wangjingfengf@163.com (J. F. Wang)

MXenes.^[34-36] And the advancement of tissue regeneration engineering by designing biomimetic scaffolds to induce the differentiation of stem cells to promote tissue repair.^[37-39] However, translation from the laboratory to the clinic still faces some challenges, including standardisation of material preparation, long-term biosafety assessment and scale-up manufacturing.^[40-42] With the deep integration of nanomedicine, artificial intelligence and materials science, MXenes will evolve towards intelligence and precision, providing transformative solutions for overcoming major medical challenges such as cancer, neurodegenerative diseases and tissue defects.^[43-45]

2. Overview of MXenes

2.1 Synthesis of MXenes

MXenes, as an emerging class of 2D transition metal carbide/nitride materials, show great potential for application in the field of biomedical engineering by virtue of their unique structural properties and excellent physicochemical properties.^[46-48] As shown in Fig. 1, the general formula of MXene is $M_{n+1}X_nT_x$ ($n=1\sim 4$), where M represents the transition metal, X is the C or N element, and T denotes the terminal chemical group.^[49] The abundant groups on the surface of MXenes,^[50] as well as its 2D layered structure endowed with a large specific surface area and adjustable layer

spacing,^[51] provide an ideal interface for drug loading and cellular interactions. Besides, the excellent electrical conductivity and photo-thermal conversion properties give it a natural advantage in the fields of tumour therapy and neurostimulation. Through innovative technological paths such as selective etching, fluorine-free etching, and insertion modulation, the synthesis process of MXenes results in precise tunability of their functionalization, laying a solid foundation for their biomedical applications.^[52-55]

Selective etching is the cornerstone of preparation of MXenes, and its technical path profoundly affects the biomedical properties of the materials. In 2011, Naguib *et al.* used hydrofluoric acid (HF) to selectively etch Al in the MAX (Ti_3AlC_2) phase for the first time at room temperature to produce MXenes with a characteristic accordion-like multilayer structure.^[56] As shown in Fig. 2a, the use of HF etching of the MAX phase remains widely used in laboratory-scale synthesis and small-scale preparation due to its high corrosivity, which demonstrably enhances reaction kinetics and yields through rapid A-layer atom stripping.^[57] But the potential biotoxicity problem should not be ignored. During the etching process, residual fluoride ions may be found on the surface or between the layers of MXenes, and these fluoride ions pose a significant risk in biomedical applications. Studies have shown that fluoride ions can

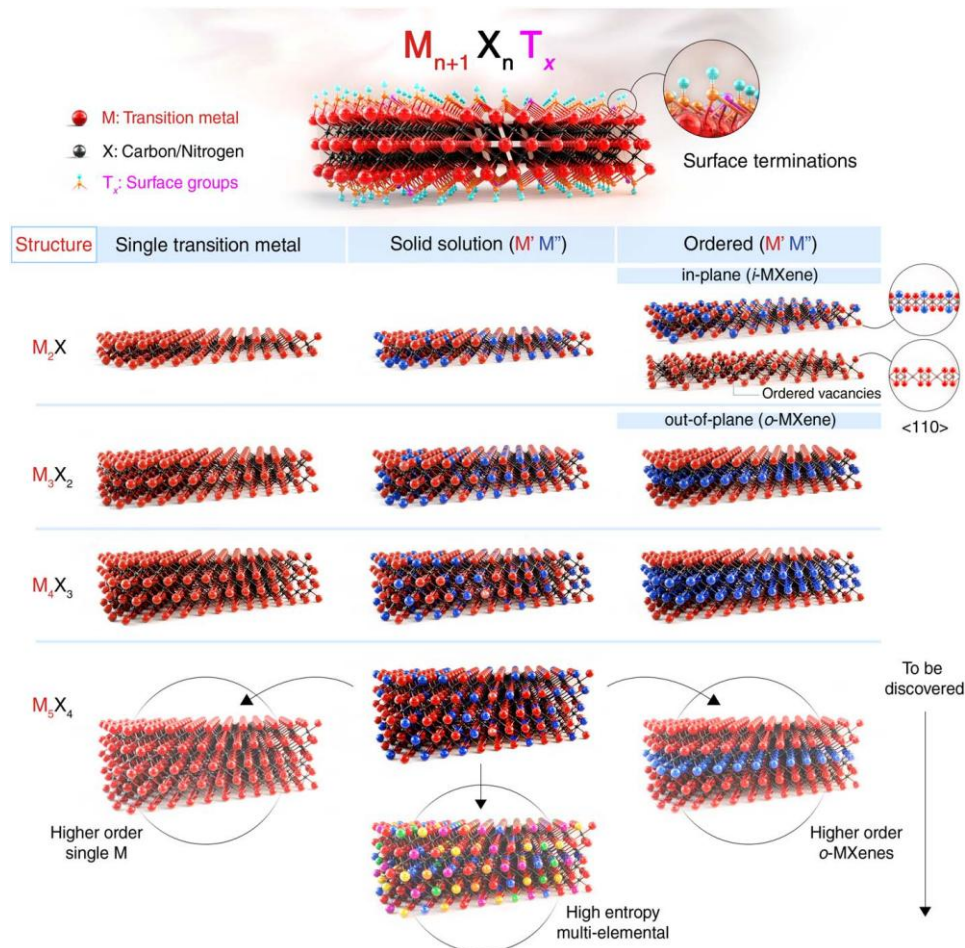


Fig. 1: The general formula of MXene, reproduced with the permission from [49], Copyright 2021 American Association for the Advancement of Science.

activate inflammatory pathways *in vivo*, triggering the activation of immune cells such as macrophages and leading to local or systemic inflammatory reactions, which could not only decrease the biocompatibility of the material, but also affect the delivery efficiency of therapeutic drugs.^[58] Therefore, residual F functional groups need to be removed by treatment before applying MXenes prepared by HF etching in organisms. However, this process may increase process complexity and affect the structural integrity of MXenes. In view of this, the development of fluorine-free etching methods or the strict regulation of HF etching conditions to balance the efficiency and biosafety for biomedical applications have become important directions in current research. To address the toxicity of fluoride ions, which is a bottleneck for the biomedical applications of MXenes, the fluorine-free etching technology has emerged and opened up a new path for the development of the field. This technology achieves precise stripping of A-layer atoms by electrochemical etching (Fig. 2b) or molten salt method (Fig. 2c),^[59,60] which avoids the introduction of F functional groups from the source and significantly improves the biocompatibility of the material.

Electrochemical etching uses electrolysis to selectively remove the A layer in the MAX phase, which is easy to regulate and generates high-purity products under mild

reaction conditions. The molten salt method enables efficient stripping of the A layer by means of the high-temperature corrosive properties of the molten salt system, which is suitable for large-scale preparation. However, it is worth noting that electrochemical etching typically requires specialized equipment such as potentiometers or galvanometers, which increases operating costs and limits large-scale implementation, while molten salt etching provides a simpler and more economical method suitable for larger scale preparation. Fluorine-free etching methods mitigate cytotoxicity risks by minimizing residual toxic species compared to HF etching, though surface terminations from these approaches may influence oxidation resistance. Such synthesis routes enable precise tuning of MXene surface chemistry, balancing electrochemical performance with biocompatibility for biomedical applications. Here, F-free MXenes has become a key material in the field of biomedical engineering by virtue of their excellent biocompatibility, electrical stability and controllable degradation properties. Their unique 2D layered structure not only provides a high signal-to-noise transmission interface for nerve electrodes, but also builds an extracellular matrix-like microenvironment in tissue regeneration scaffolds, which significantly facilitates the tissue repair process. The surface charge, hydrophilicity

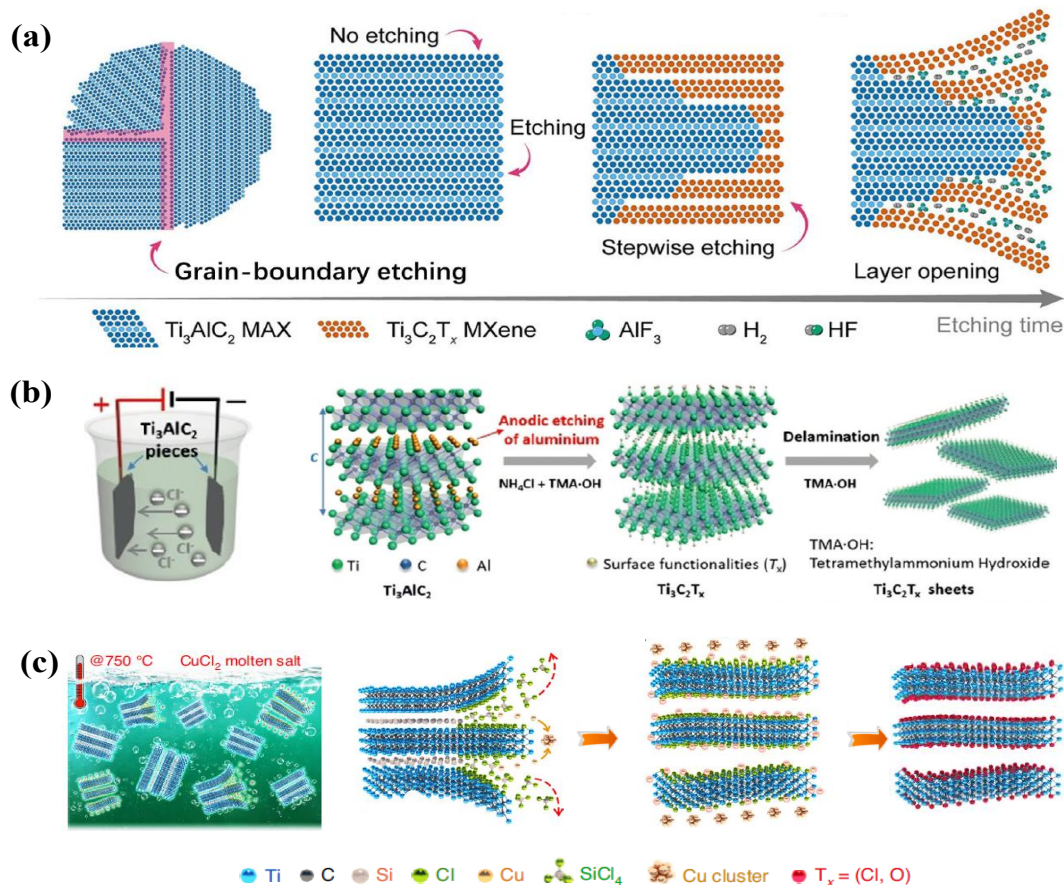


Fig. 2: a) Schematic of MXenes prepared by HF etching method. a reproduced with the permission from [57], Copyright 2022 American Chemical Society. b) Schematic of MXenes prepared by electrochemical etching, b reproduced with the permission from [59], Copyright 2018 John Wiley and Sons. c) Schematic of MXenes prepared by molten salt method, c reproduced with the permission from [60], Copyright 2020 Nature Publishing Group.

and biorecognition properties of MXenes can be precisely regulated by introducing different surface functional groups, such as specific chemical groups or biomolecules, which can further expand the boundaries of their applications in cutting-edge fields such as controlled drug release systems, cell-targeted delivery and smart biosensors, showing the infinite possibilities of the functional design of MXenes.^[61-63]

2.2 Properties of MXenes

The 2D layered structure of MXenes gives them an extraordinarily large specific surface area and abundant surface sites, providing an ideal microenvironment for cell attachment and material exchange. The nanoscale thickness allows MXenes to be bent, folded and adapted to the geometry of complex biological tissues (Fig. 3a).^[64] The MXenes nanosheets were subjected to interlayer spacing modulation to design an MXenes-based catalytic system, which is capable of rapid electron transfer and formation of activated state complexes with peroxyxynitrite. This catalytic system demonstrated efficient pollutant degradation in a continuous flow treatment device, and showed strong adaptability to a variety of antibiotics and complex aqueous environments. In addition, it exhibited very low metal leaching during the catalytic process, combining treatment efficiency with environmental friendliness.

While MXenes share graphene's high electrical conductivity, their tunable surface terminations confer hydrophilicity and active electrochemical sites, enabling superior dispersion in polar solvents and functional versatility. MXenes' surfaces can be designed with a rich variety of

functional groups (Fig. 3b),^[49] and these can effectively determine their biocompatibility and functionalisation potential. The surface functionalization of MXenes nanosheets allows their multi-disciplinary applications. For example, in the tumour therapy, surface charge modulation may allow MXene nanosheets to penetrate the vessel wall and target the tumour microenvironment, providing precise navigation for drug delivery. This controllability of surface chemistry provides a molecular-level means of regulating MXenes for diverse applications in biomedicine.

As shown in Fig. 3c, MXenes also have excellent photothermal conversion efficiency due to their unique 2D layered structure, strong electromagnetic wave absorption capacity, and localized surface plasmon resonance effects,^[65] which is significantly higher than traditional materials such as gold nanorods. In the field of biomedical engineering, the plasmonic resonance effect formed by its 2D structure confines the thermal energy of heat generated by near-infrared radiation (NIR) to the surface of the nanosheets, achieving local high temperature killing of tumour cells with minimal damage to the surrounding normal tissues. After targeted molecular modification, MXenes nanosheets can synergistically combine mild photodynamic therapy with chemodynamic therapy to eradicate tumours very effectively, without causing any significant tissue damage. This photothermal treatment strategy not only reduces the systemic toxicity of chemotherapeutic agents, but also activates anti-tumour immune responses in conjunction with immunotherapy. The photothermal properties of MXenes are driving the development of oncology treatments towards precision and efficiency.

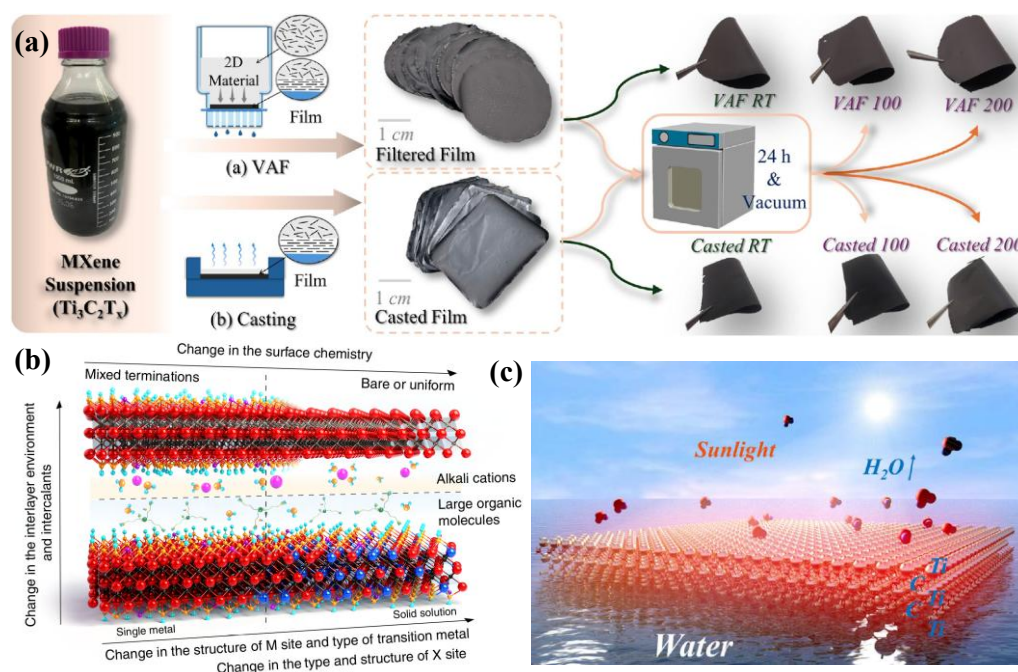


Fig. 3: a) Schematic diagram of mechanical properties of MXene, a reproduced with the permission from [64], Copyright 2025 Elsevier. b) Abundant functional groups of MXene, b reproduced with the permission from [49], Copyright 2021 American Association for the Advancement of Science. c) Photothermal conversion properties of MXenes, c reproduced with the permission from [65], Copyright 2017 American Chemical Society.

Additionally, MXenes exhibit high electrical conductivity stemming from robust metallic bonding of transition metal atoms within their 2D lattice and surface functional group-mediated interlayer electron transport pathways. The metal-like conductivity of MXenes gives it a natural advantage in the field of neuroelectrodes.^[66-68] The charge transfer resistance of high-purity MXene films can be effectively reduced after nanostructuring. In brain-computer interface applications, MXenes-based electrodes can record neuronal electrical signals with high fidelity and improve the signal-to-noise ratio by a factor of one.^[69-71] In addition, the flexible nature of MXenes allows them to form a conformal contact with neural tissue, reducing inflammatory responses and providing a long-term stable recording and stimulation interface for chronic neurological disease treatment.^[72-74] This synergy of conductivity and flexibility provides material support for performance breakthroughs in neuroengineering devices. As shown in Table 1, the fundamental properties of MXenes and their biomedical potential are demonstrated. At the synthesis method level, the advantages and disadvantages of traditional hydrofluoric acid etching are compared with those of the emerging F-free etching technology, which significantly enhances the biocompatibility of the material through electrochemical or molten salt methods. In terms of structural properties, the 2D layered architecture of MXene gives them a large specific surface area and tunable layer spacing, which, combined with the abundance of functional groups on the surface,^[75-77] provides an ideal interface for drug loading and cellular interactions. Their metal-like conductivity and excellent photothermal conversion properties show unique

advantages for neuroelectrodes and oncology therapeutics.^[78,79] The current challenges mainly lie in balancing F residues with synthesis efficiency and developing degradable MXenes to advance clinical translation.

3. Applications in biomedical engineering

3.1 Drug delivery and tumour therapy

MXenes show unique advantages as drug delivery carriers in oncology therapy.^[80-82] MXenes nanosheets have a higher specific surface area, which is expected to achieve efficient drug loading through π - π stacking or electrostatic interaction, and their interlayer channels can also effectively block the sudden release of the drug to achieve a long-term delayed release effect.^[83-85] This spatio-temporally controlled release property significantly reduces systemic toxicity and provides a new approach for tumour chemotherapy.

The photothermal conversion capability of MXenes makes them uniquely valuable in synergistic oncology treatments.^[86-88] Under NIR irradiation, free electrons on the surface of MXenes generate collective oscillations, converting optical energy into thermal energy, and the local temperature can be rapidly increased to higher than 50°C. This photothermal effect not only directly induces apoptosis of tumour cells, but also triggers the rupture of heat-sensitive liposomes or the dissociation of DNA nanogels, which enables the precise release of drugs at the tumour site. Glioblastoma is a highly aggressive brain tumour, and its traditional treatments are often limited by the tumour's low sensitivity to radiotherapy and by damage to surrounding tissues. As shown in Fig. 4a, scientists developed an MXene-based thermosensitive

Table 1: MXenes fundamentals and biomedical potential.

Category		Properties	Features	Biomedical applications	References
Synthesis	Selective Etching	Al layer removal from MAX phases with HF	Fluoride ion residues risk inflammation	Drug delivery systems, neural electrodes	[49, 57]
	Fluorine-Free Etching	Electrochemical/Molten Salt Methods, etc	Avoids fluoride introduction Scalable for industrial production	Enhanced biocompatibility in implants	[59, 60]
	2D Layered Architecture	Ultra-thin nanosheets, tunable interlayer spacing	High surface area for drug loading Flexible conformal contact with tissues	Tissue engineering scaffolds, biosensors	[28, 29]
Properties	Surface Functional Groups	-F, -OH, -O-	Terminal group engineering for targeted delivery	Cancer therapy, neural interfaces	[34, 35]
	Conductivity	Charge transfer resistance reduction	SNR improvement in neural recording Flexible electrodes for chronic implants	Brain-machine interfaces, neuroprosthetics	[38, 39]
Challenges	Photothermal Conversion	NIR-triggered hyperthermia	Thermal efficiency surpasses gold nanorods. Localized tumor ablation	Synergistic photothermal-chemo therapy	[41, 42]
	Safety & Degradability	Long-term degradation Immune responses	Biodegradable MXene development. Immunotoxicity assessments	Critical for clinical translati	[44, 45]

nanoplatforM for radiotherapy.^[89] The extensive surface area of MXenes was utilised to anchor gold nanorods and cisplatin. This significantly enhances the efficacy of radiotherapy and photothermal therapy, achieving effective tumour cell killing and significantly improving the tumour microenvironment. The combination of radiotherapy sensitisation, cisplatin-mediated chemotherapy and α PD-1 induced a strong immunogenic cell death effect, providing a spatio-temporally coordinated approach with enhanced efficacy and safety compared to conventional therapies.

Besides, early surgical resection and chemotherapy are commonly used for the treatment of bone tumours, but preventing recurrence and filling bone defects caused by the resection site remain highly challenging. The photothermal conversion capability of MXenes also makes them useful in the synergistic treatment of bone tumours. As shown in Fig. 4b, composite of 2D ultrathin Nb₂C-MXene nanosheets into 3D printed bioglass scaffolds (NBGS) can be effectively used for the treatment of osteosarcoma.^[90] The 2D Nb₂C-MXene is photoresponsive in the second NIR biowindow and has a high tissue penetration depth, enabling the 3D-printed composite to effectively kill bone cancer cells. In addition, this material significantly promotes vascular neovascularisation. Calcium and phosphate released during scaffold degradation can promote the mineralisation of new bone tissue. This Nb₂C-MXene based composite scaffold with multiple functions such as killing bone tumour cells, promoting vascular

neovascularisation and bone regeneration is an implantable biotherapeutic repair material with good efficacy against bone tumours.

In addition, the specificity of the tumour microenvironment provides a biological target for smart response delivery of MXenes. The surface of MXenes can be modified with nano-enzymes or redox-responsive moieties to achieve triggered release by taking advantage of the hypoxia and high glutathione concentration in tumour tissue. For example, nanoenzymes have the enzymatic activity and physicochemical properties of nanomaterials. However, the low activity of nanoenzymes in the tumour microenvironment results in limited therapeutic efficacy. The use of MXenes integrated nanoenzymes exhibiting dual catalytic activity can exert synergistic effects to enhance tumor therapy.^[91] MXene-integrated nanoenzymes consist of CeO₂ nanoenzymes loaded on MXenes with dual enzyme-like activities. In such constructs, the catalase and peroxidase-like activities of CeO₂ nanoenzymes attenuate hypoxia and enhance oxidative stress in the tumour microenvironment, and overexpressed glutathione is depleted by redox reactions of CeO₂ nanoenzymes. MXenes loaded with CeO₂ nanoenzymes could combine photothermal effects and dual enzyme-like activities, leading to enhanced tumour nanocatalytic therapy with a tumour growth inhibitory effect of 92%, which is of high value for the development of nano-enzymatic catalytic therapy. Although MXenes show great potential in the field of tumour

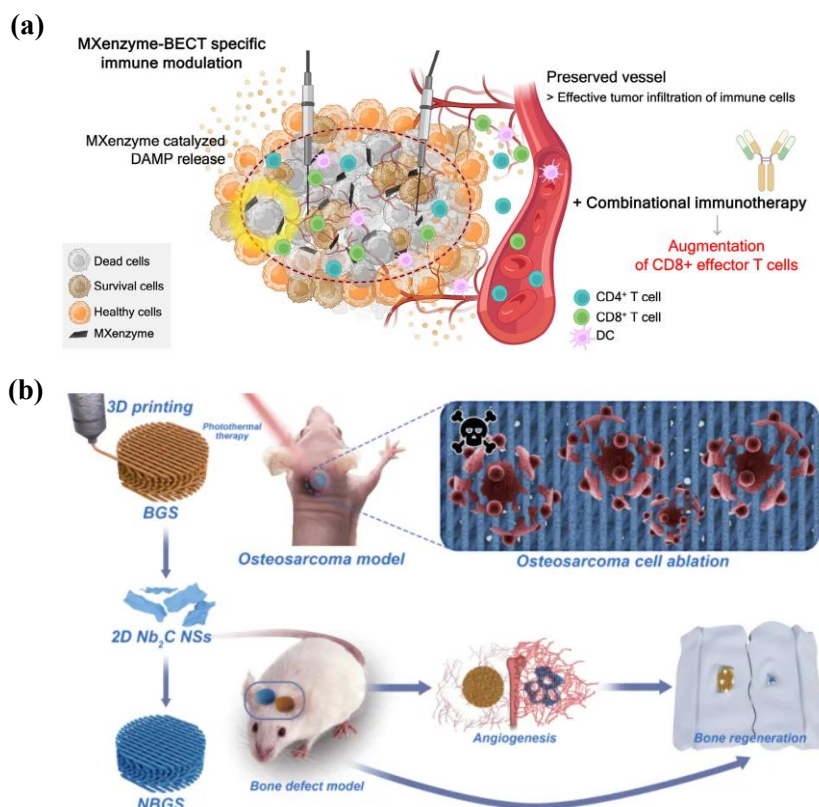


Fig. 4: a) MXenes-based drug-loaded nanoplatforM, a reproduced with the permission from [89], Copyright 2025 John Wiley and Sons. b) 3D printed MXenes-based bioscaffolds for osteosarcoma treatment, b reproduced with the permission from [90], Copyright 2025 Nature Publishing Group.

therapy, their biosafety still needs to be systematically evaluated. MXenes nanosheets are mainly metabolised by the liver and gallbladder, but the degradation cycle is long and may trigger an inflammatory response. In order to solve the above problems, the research of MXenes needs to focus on the development of degradable materials. Besides, the association of MXene complexes with immune checkpoint inhibitors should be explored to construct a multifunctional platform integrating targeted therapy and immune activation, which will provide an innovative solution for precise tumour treatment.^[92-94]

3.2 Bio-detection and sensing

The unique physicochemical properties of MXenes promise them great potential in biosensing.^[95-97] Their metal-like conductivity combined with quantum domain-limiting effect enables the construction of electrochemical biosensors for the ultra-sensitive detection of various biomarkers. The 2D MXenes exhibit a remarkable area polarisation effect at the planar interface, and is able to achieve efficient targeted adsorption of phenolic compounds through the π - π interaction of benzene rings, which in turn catalyze their electrochemical oxidation process. In addition, the intelligent colourimetric sensing platform based on the CRISPR-Cas12a system enables highly specific visual detection of hepatitis B virus (HBV) nucleic acids through the synergistic interaction of MXene nanosheets and Ag/Pt bimetallic nano hybrids (Fig. 5a).^[98] The innovative system utilises the trans-cutting activity of Cas12a protein as a molecular switch. When the HBV target is present, the Cas12a crRNA complex is activated and specifically degrades the reporter probe DNA. This process effectively inhibits the metallation of the DNA template on the surface of MXenes, while blocking the adsorption of enzyme activity enhancer DNA, resulting in a significant decrease in the catalytic performance of the nano hybrids. By monitoring the colour change of the reaction system, combined with a smartphone image acquisition system, quantitative visual detection of HBV DNA can be achieved. This technology integrates the precise recognition ability of gene editing tools, the advantage of large specific surface area of MXenes and the signal amplification effect of bimetallic nanostructures to achieve femtomole-level detection sensitivity and single-base mismatch recognition as well as maintaining the ease of operation of traditional colorimetric methods, providing a revolutionary solution for viral nucleic acid screening in the context of prompt oncology testing scenarios.

MXenes possess graphene-like levels of electron conductivity, a specific surface area several times that of graphene oxide, and tunable surface chemistry. Their layered structure enables efficient loading of biorecognition molecules, while their rich functional groups provide a flexible interface for molecular modification. In biosensing, MXenes can directly participate in electrochemical/optical reactions as signal conversion elements and significantly enhance the catalytic performance of metal nanoparticles or quantum dots

as nanocarriers, and this dual role gives them a natural advantage in constructing cascade signal amplification systems. MXenes enable the construction of a self-adhesive composite hydrogel epidermal sensing system with biomimetic skin properties (Fig. 5b).^[99] Through a dual-network synergistic assembly strategy, conductive nanosheet arrays are molecularly composited with biocompatible hydrogel matrices to form a smart epidermal interface that combines excellent adhesion properties and UV shielding. The interface can adaptively fit the microtexture of human skin to achieve high-fidelity acquisition of physiological electrical signals. Its unique 3D porous network structure not only ensures that the contact impedance between the electrode and the skin is two orders of magnitude lower than that of traditional dry electrodes, but also maintains a signal-to-noise advantage of greater than 30 dB under dynamic motion scenarios, providing a novel hardware foundation for precision medical monitoring and brain-computer interaction interfaces. The myoelectric signal decoding platform constructed based on this system successfully realises real-time classification and recognition of complex sign language movements by integrating the convolutional neural network algorithm, and achieves 98.6% recognition accuracy in the validation set containing 12 types of gestures, which provides a revolutionary solution for the barrier-free communication of hearing-impaired people.

In addition to sensing applications, MXenes-based functionalized hydrogels can exhibit multimodal biomedical properties. The inherent antimicrobial activity conferred by their layered structure can effectively inhibit staphylococcus aureus biofilm, while the good histocompatibility and rapid coagulation response show the potential for applications in the field of combat trauma care. This smart epidermal system integrating sensing, protection and treatment functions opens up a new path for the deep integration of wearable medical devices and artificial intelligence-assisted healthcare. The good biocompatibility and solution processability of MXenes enable them to be seamlessly interfaced with microfluidic chips and flexible electronic devices, which provides a material basis for the development of portable instant diagnostic devices.^[100-102] The application of MXenes not only promotes the technological innovation of ultra-trace detection of disease markers, but also opens up a new paradigm in the field of biosensing from “detection in laboratory precision” to “daily health monitoring”, which is of milestone significance for precision medicine and on-site detection.

3.3 Tissue engineering and regenerative medicine

The application of MXenes in the field of tissue engineering stems from its unique coupling of mechanical and electrical properties.^[103-105] In the field of bone regenerative medicine, MXenes show excellent osteoinductive properties. By using MXenes, intelligent drug release nanocomposite hydrogel systems can be constructed to achieve bone tissue repair. As shown in Fig. 6a, a thermal-sensitive bioactive scaffold was

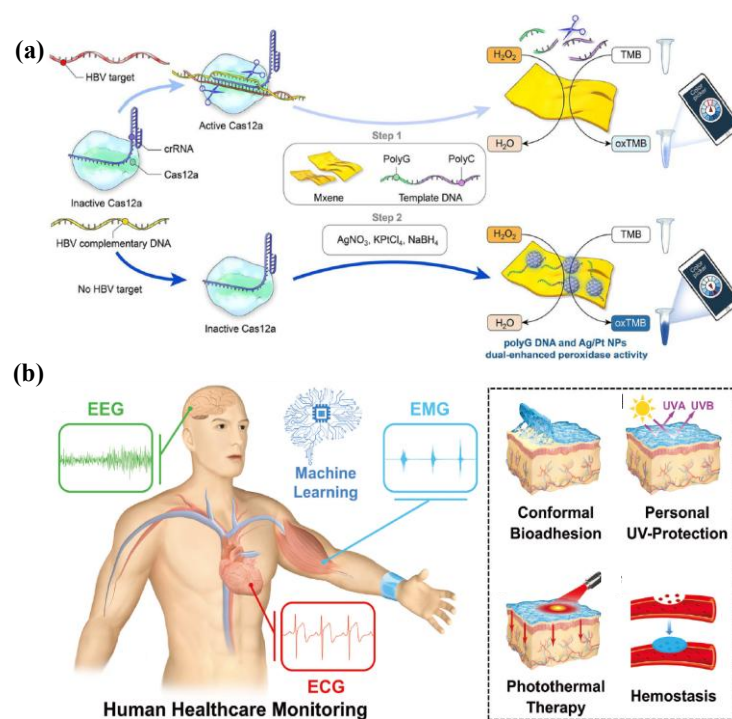


Fig. 5: a) Application of MXenes in biodetection, a reproduced with the permission from [98], Copyright 2022 Elsevier. b) Application of MXenes in biosensing, b reproduced with the permission from [99], Copyright 2024 John Wiley and Sons.

formed by in situ loading dexamethasone (Dex) on MXenes.^[106] This system exhibited a dual response mechanism, where the hydrogel network underwent a reversible phase transition under the microenvironmental warming condition of 42 °C induced by NIR irradiation, triggering a pulsatile release of Dex. At the same time, the photo-thermal conversion property of MXenes synergistically interacted with the osteogenic activity of Dex, which significantly activated the anti-apoptotic pathway of bone-derived mesenchymal stem cells and promoted the expression of osteogenic genes. In vitro experiments showed that after programmed NIR activation, the hydrogel-induced mineralisation of bone nodules was 3.2-fold higher than that of the thermal stimulation or drug-treated group alone, demonstrating bone regeneration efficacy beyond that of conventional combinatorial strategies. This spatially and temporally controllable photothermal-drug synergistic therapeutic strategy not only achieves sub-millimetre precision release of high-temperature-sensitive drugs, but also dynamically adjusts the therapeutic parameters through a non-invasive radiation window, which provides a new paradigm with clinical translation potential for precise bone tissue engineering.

In the field of neural repair, the conductive network of MXenes can provide directional guidance for neuronal synaptic extension. As shown in Fig. 6b, by integrating a decellularised umbilical cord (DUC) matrix with a hollow-structured gelatin methacrylated gelatin (GelMA)/titanium carbide MXene composite hydrogel catheter, an advanced nerve conduit was developed that is expected to optimise the repair of the sciatic nerve after injury.^[107] The new DUC-MXene-GelMA catheter exhibits excellent mechanical

properties, electrical conductivity characteristics and biocompatibility. Thanks to the synergistic effect of DUC and MXenes, the catheter exhibits significant biological advantages in stimulating neurite extension and promoting the proliferation and migration of schwann cells. Based on in-vivo studies in a rat sciatic nerve injury model, the DUC-MXene-GelMA catheter effectively supports axonal regeneration and accelerates motor function recovery. In addition, MXenes can be used as drug carriers to achieve controlled release of nerve growth factors, further accelerating the nerve repair process. These properties together establish MXenes as a core material for the construction of intelligent nerve repair materials, opening up a new pathway for the development of next-generation neural tissue engineering strategies.

Although MXenes show great potential in the field of tissue engineering and regenerative medicine, their clinical translation still needs to overcome some challenges.^[108-110] Firstly, the in-vivo degradation rate of MXenes does not match the bone regeneration cycle, and the spatio-temporal controlled decay of the scaffold mechanical properties can be achieved by introducing degradable metal elements such as Mg and Zn. Secondly, the immunoregulatory mechanism of MXenes is still unclear, and surface modification of immune checkpoint inhibitors can construct immune microenvironment-friendly scaffolds. Finally, the large-scale preparation process needs to be optimised, and the currently developed roller-type liquid-phase stripping technology has achieved the continuous production of gram-scale MXene nanosheets. The development of MXene-based smart scaffolds integrated with controlled drug release, electrical stimulation, and biosensing will promote tissue engineering

towards precision and personalisation.^[111-113]

3.4 Antimicrobial and anti-infective

The antimicrobial activity of MXenes mainly stems from their unique 2D layered nanostructures and multimodal mechanisms of action.^[114-116] As shown in Fig. 7a, their sharp edge structures can directly disrupt the integrity of bacterial cell membranes through mechanical stress, producing a physical bactericidal effect.^[117] The high specific surface area synergises with the abundance of free radical sites on the surface to significantly enhance the photothermal conversion capability, a property that enables them to effectively convert optical into thermal energy. In particular, the Joule heating effect triggered by the high density of carriers on the surface further strengthens the photothermal antimicrobial properties of MXenes. This photothermal property not only accelerates the activation of the intrinsic antimicrobial mechanism, but also enhances the overall antimicrobial efficacy through the nanoscale heat conduction effect. In the dispersed system, the colloidal stability of MXenes becomes a key influencing factor, and the aggregation and precipitation will lead to the reduction of the effective action area, thus decreasing the antimicrobial efficiency. Currently, the introduction of chelating ligands has been proven to be an effective strategy to enhance the

dispersion stability of MXenes. It is worth noting that the chemical stability of MXenes in the aqueous phase is inherently flawed. Hydrolysis reactions and dissolution of oxygen will trigger oxidation, gradually changing their 2D structures to metal oxide particles. This morphological transformation leads to the reduction of sharp edges and consequent decrease in antimicrobial activity. To address this problem, surface modification of antimicrobial active molecules not only protects MXenes from oxidation, but also enhances the stability and antimicrobial properties of the materials through synergistic effects. The antimicrobial efficacy of MXenes is a combination of their physical structure, electronic properties and chemical stability, and future research should focus on their surface engineering to balance the antimicrobial activity and material stability, and to promote their practical applications in the biomedical field.

MXenes have demonstrated unique advantages in multi-mechanism synergistic antimicrobial activity and promotion of diabetic wound repair in the constructed composite hydrogel system.^[118-120] As shown in Fig. 7b, their intrinsic 2D layered structure not only directly destroys the integrity of bacterial membranes through the sharp edge effect, but also generates a controllable photo-thermal effect triggered by NIR irradiation, forming a thermo-chemical synergistic

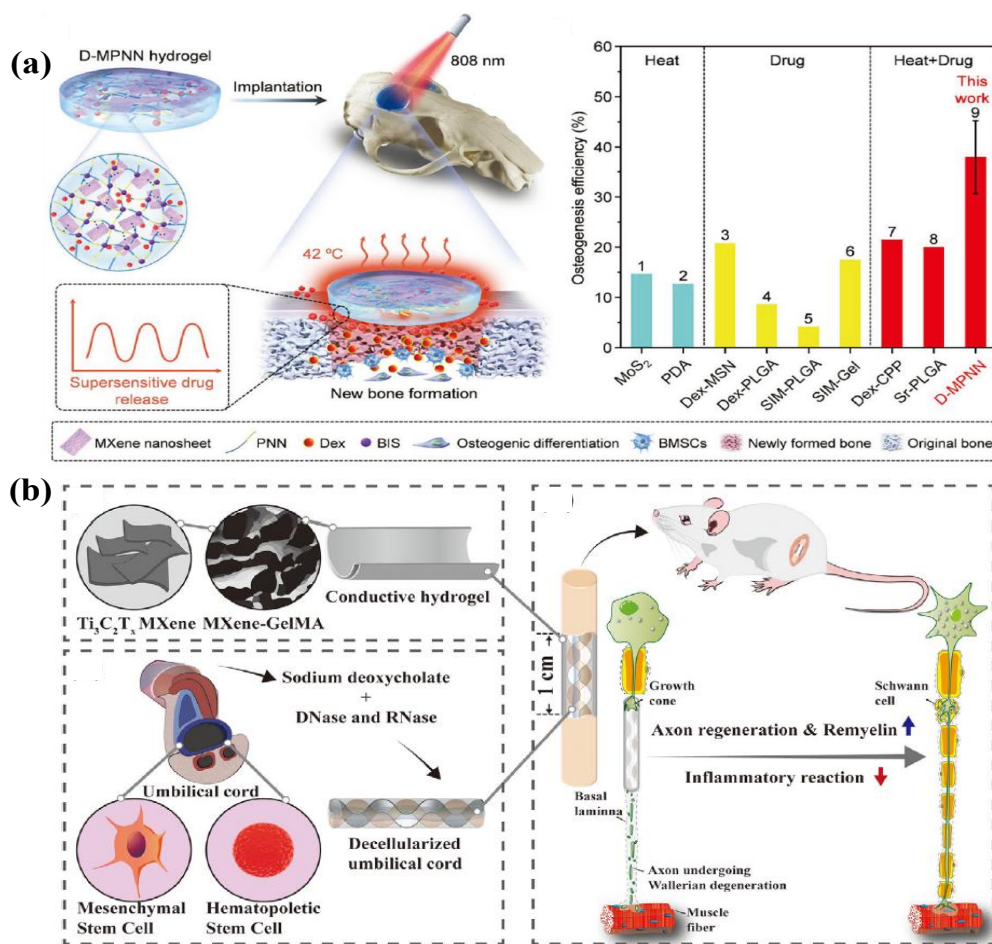


Fig. 6: a) Application of MXenes in tissue engineering, a reproduced with the permission from [106], Copyright 2024 John Wiley and Sons. b) Application of MXenes in regenerative medicine, b reproduced with the permission from [107], Copyright 2025 John Wiley and Sons.

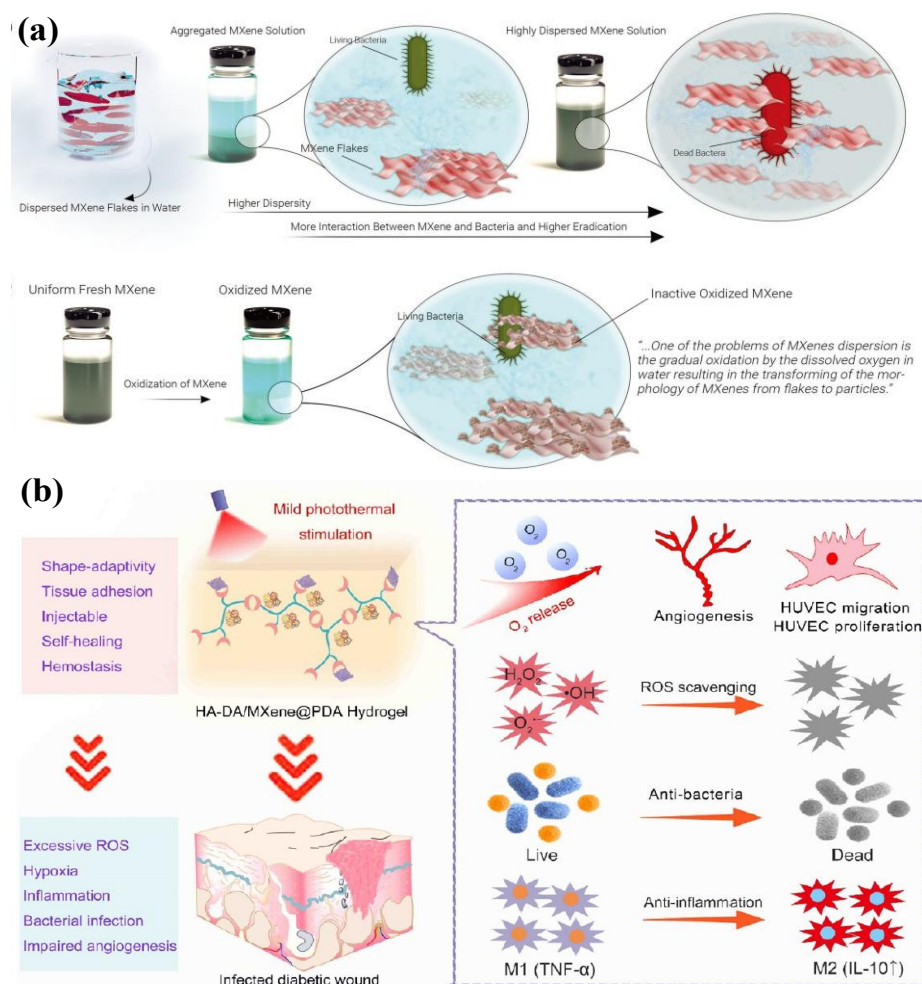


Fig. 7: a) The antimicrobial properties of MXenes, a reproduced with the permission from [117], Copyright 2023, John Wiley and Sons. b) The anti-infection performance of MXenes, b reproduced with the permission from [121], Copyright 2022 American Chemical Society.

bactericidal mechanism with the $\text{HbO}_2/\text{H}_2\text{O}_2$ catalytic system.^[121] The stable photo-thermal property of MXenes ensures controlled activation of oxygen carriers and maintains oxidative balance of the microenvironment of the wounds while repeatedly supplying oxygen. More critically, MXenes, as an artificial non-enzymatic antioxidant, can effectively scavenge reactive oxygen species/reactive nitrogen species and form a cascading antioxidant barrier with the dopamine coating, significantly reducing the inflammatory cascade triggered by oxidative stress. This multilayered antimicrobial-antioxidant-anti-inflammatory synergism, together with the regulation of macrophage polarisation, builds up an active defence network in the microenvironment of diabetic wound infections. The cross-linking of MXene nanosheets and injectable hydrogel not only confers them with self-healing properties, but also forms positive feedback with their photothermal enhanced cell activity and controlled release of biological oxygen, accelerating the proliferation and migration of endothelial cells, and ultimately achieving the goal of wound repair and migration.

Despite the promise of MXenes for antimicrobial applications, some key challenges still need to be addressed.

Current research reveals that oxidation of MXenes in physiological environments leads to the attenuation of antimicrobial properties, and the stability can be significantly enhanced by surface coating with SiO_2 or polydopamine. More noteworthy is the immunomodulatory property of MXenes, whose degradation product, Ti ions, can activate the polarisation of macrophages polarization and enhance the local immune response. MXenes-based composite antimicrobial coatings should be developed as well as the construction of smart antimicrobial systems that can respond to the infected microenvironment. With the breakthrough in large-scale preparation technology for MXenes, they hold significant clinical translational value in the fields of implantable device coating and postoperative anti-infection.^[14,122,123]

3.5 Other cutting-edge applications

MXenes also show good application prospects in the field of organoid engineering and genetic engineering. Through the Joule thermal effect, they can be used to achieve precise thermal regulation of organoid systems, which provides an innovative tool for the study of the dynamic function of

complex organoids such as the heart and intestines. Their knittable characteristics support the construction of 3D biological assemblies, promoting the development of organoid engineering in the direction of integration and intelligence. As shown in Fig. 8a, the researchers cleverly used the stress modulation and solidification bath induction during spinning to achieve the radial orientation alignment of MXenes nanosheets to prepare MXene/CNFs composite fibre artificial muscles (MFAMs).^[124,125] This structure endowed the material with extraordinary mechanical output in a wide temperature domain from 25 °C to 125 °C, capable of lifting objects a thousand times its own weight with a maximum contraction stroke of 21% and a work capacity of up to 1.76 J/g, which far exceeded the natural muscle performance. The driving mechanism originates from the temperature-induced hydrogen bonding network rearrangement, which compresses the spacing of MXenes nanosheets and reduces the porosity to produce efficient contraction response. The excellent Joule-heat and photothermal conversion properties of MXenes enable MFAMs to exhibit fast and stable driving characteristics under electro-thermal and photothermal stimulation, which is a significant advantage over the traditional thermally-driven fibre artificial muscles. This energy conversion efficiency and driving stability provide an ideal solution for precise thermal regulation and dynamic behavioural simulation in organoid models. More critically, the non-twisting structure of MXenes composite fibres gives them a high degree of knittability, enabling the construction of complex 3D actuation networks, such as smart grippers or bionic prostheses integrated with multiple fibres. Under the irradiation of 808 nm NIR laser, these devices can achieve more than 200 cycles of actuation, demonstrating the durability and functional complexity required for organ-like engineering. This kind of research not only expands the

application of MXenes in the field of bionic actuation, but also provides a material basis for the development of organoid systems, intelligent prostheses, and flexible robots with autonomous locomotion, marking an important step towards dynamic functional simulation in organoid engineering.

In the field of gene editing, MXenes show unique delivery advantages.^[98,126,127] As shown in Fig. 8b, researchers developed a boolean logic-gated gene editing system by combining the efficient photothermal conversion property of MXenes with the programmability of functional nucleic acids.^[125] The system takes advantage of the local thermal effect generated by MXene vector triggered by NIR to form multi-signal inputs with biomarkers such as tumour-specific miRNAs, and precisely controls the spatiotemporal release of complexes through nucleic acid chain substitution reaction. In the logic gate design, MXenes vectors have demonstrated the ability to finely regulate the gene editing process, which not only achieves intelligent response editing in living cells, but also achieves targeted knockdown of the gene in tumour models through the ‘AND’ logic gate to induce apoptosis of tumour cells and inhibit the growth of tumours effectively. This multimodal stimulus response mechanism enables the gene editing system to make intelligent decisions based on endogenous and exogenous signals, significantly improving therapeutic precision. The photothermal property of MXenes not only serves as a trigger switch, but also enhances the efficiency of gene editing by generating thermal stress in the microenvironment, resulting in a synergistic thermal-genetic intervention effect. This study verifies the high efficiency and safety of MXenes in gene delivery systems, and realises the leap of gene editing from ‘static execution’ to ‘dynamic response’ through the boolean logic regulation strategy, which provides a spatio-temporally controllable and intelligent solution for cancer treatment and genetic disease correction,

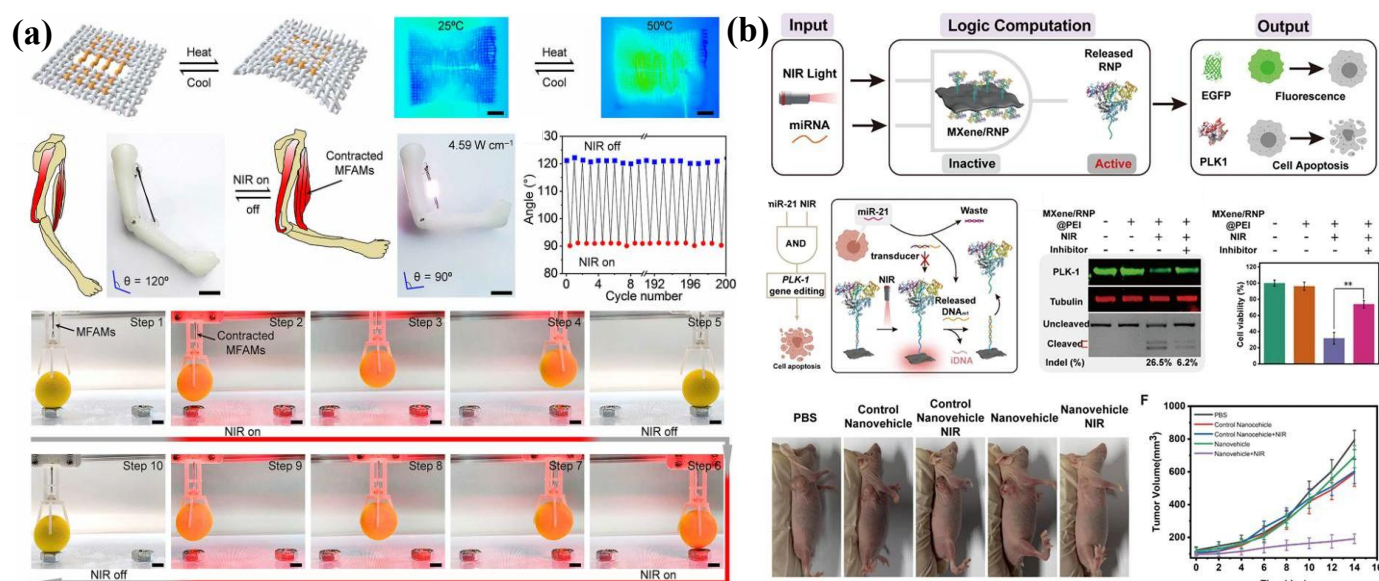


Fig. 8: a) Application of MXenes in organoid engineering, a reproduced with the permission from [124], Copyright 2025, American Association for the Advancement of Science. b) Application of MXenes in genetic engineering, b reproduced with the permission from [125], Copyright 2022 Nature Publishing Group.

Table 2: Advanced Biomedical Applications of MXenes.

Applications	Form	Treatment system	Innovations	Translational potential	References
Oncology Therapeutics	Photothermal-Chemo Synergy	NIR-II responsive scaffolds with osteogenesis promotion	3.2x bone nodule mineralization. Vascularization enhancement	Orthotopic bone tumor treatment	[106]
	Nanozyme-MXene Hybrids	Dual-enzyme mimicry with ROS modulation	92% tumor growth inhibition. GSH depletion strategy	Enhanced oxidative stress therapy	[91]
Biosensing & Diagnostics	CRISPR-Cas12a Colorimetric Platform	HBV DNA detection via MXene-Ag/Pt nanohybrids	Femtomolar sensitivity Single-base mismatch recognition	POCT applications in viral screening	[98]
	Epidermal Sensing Hydrogels	Self-adhesive MXene-hydrogel composites	98.6% sign language recognition. 30dB SNR improvement	Wearable health monitoring	[99]
Tissue Engineering	NIR-Triggered Drug Release	Spatiotemporal drug delivery via photothermal phase transition	2.8x Bcl-2/Bax ratio increase. Synergistic osteogenesis	Precision bone regeneration	[125]
	Neural Conduits	Axonal regeneration support with electrical conductivity	Accelerated motor function recovery. Schwann cell proliferation	Peripheral nerve repair	[107]
Anti-Infection Strategies	Multimodal Antimicrobial Hydrogels	Synergistic physical/photothermal/chemical bactericidal effects	ROS/RNS scavenging. M1 macrophage polarization	Diabetic wound healing	[121]
Frontier Innovations	Organoid Engineering	Thermal-responsive artificial muscles with 21% contraction strain	1.76 J/g work capacity. 200+ cycle durability	Dynamic tissue models, soft robotics	[124]

and pushes forward the development of gene editing technology in the direction of intelligence and precision. With the research development, MXenes are expected to be integrated with gene wiring, synthetic biology and other cutting-edge technologies to build a closed-loop gene regulation system, further expanding the boundaries of genetic engineering applications. As shown in Table 2, cutting-edge application innovations of MXenes in biomedical engineering are demonstrated. These include oncology therapeutic areas, biosensing directions, tissue engineering aspects, and antimicrobial applications, all of which highlight the clinical translational potential of MXenes.

4. Conclusion and perspectives

MXenes are setting a paradigm shift in the field of biomedical engineering by virtue of their unique atomic-level thickness, large specific surface area and metal-like conductivity. The multimodal interfacial modulation capability conferred by their 2D layered structure enables ultra-efficient drug loading and controlled release in drug delivery systems, single-molecule detection sensitivity in biosensing interfaces, as well as inducing directional cellular differentiation through electroactive stimulation in tissue regeneration scaffolds. This cross-scale material-biological synergy breaks through the functional boundaries of traditional biomaterials and demonstrates the great potential of integrated diagnostic and

therapeutic platforms.

However, there are still some challenges in moving from laboratory innovation to clinical translation. Firstly, biosafety studies need to establish a multi-level assessment system from cell to tissue to organ, and systematically elucidate the metabolic pathways of MXenes degradation products and long-term immunoregulatory networks. Secondly, the functionalization modification faces the contradiction between ligand coupling efficiency and stability, which requires the development of efficient surface engineering strategies, as well as the solution of the technical bottleneck of lattice defect control in the scale-up preparation. Finally, the clinical translation pathway urgently needs to build a standardised nanotoxicology database and promote the iterative upgrading of the regulatory science framework to fit the special physicochemical properties of 2D materials.

As research on MXenes in the field of biomedical engineering continues to deepen, stimulus-responsive smart interfaces can be constructed through surface molecular engineering to achieve precise spatio-temporal regulation of drug release, gene editing and other functions. For example, integrating MXenes into the next generation of flexible electronic products, AI driven surface terminal design for customized functionality, and scalable fluorine free synthesis routes to promote sustainability. In addition, the material properties of MXenes can be integrated with artificial

intelligence and microfluidic technology to develop an integrated platform for multimodal diagnosis and treatment. With the in-depth analysis of the mechanism of material-biological interface, the establishment of multidisciplinary collaborative network and the innovation of translational medicine models, MXene-based nano platforms are expected to play a transformative role in the precise treatment of tumours, complex tissue regeneration and other medical challenges, and promote biomedical engineering into the era of intelligence and integration.

Acknowledgments

This work was supported by Excellent Youth Program of Scientific Research Fund of Hunan Provincial Department of Education (Grant No. 24B0519), National Natural Science Foundation of China (Grant No. 52203145), Young Talent Fund of Association for Science and Technology in Shaanxi China (Grant No. 20230428), Qinchuangyuan Citing High-level Innovation and Entrepreneurship Talent Projects (Grant No. QCYRCXM-2022-190), and Youth Program of Hunan Provincial Natural Science Foundation (No. 2024JJ6201).

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

- [1] H. Huang, W. Feng, Y. Chen, Two-dimensional biomaterials: material science, biological effect and biomedical engineering applications, *Chemical Society Reviews*, 2021, **50**, 11381-11485, doi: 10.1039/D0CS01138J.
- [2] S. E. A. Gratton, S. S. Williams, M. E. Napier, P. D. Pohlhaus, Z. Zhou, K. B. Wiles, B. W. Maynor, C. Shen, T. Olafsen, E. T. Samulski, J. M. DeSimone, The pursuit of a scalable nanofabrication platform for use in material and life science applications, *Accounts of Chemical Research*, 2008, **41**, 1685-1695, doi: 10.1021/ar8000348.
- [3] B. M. Holzapfel, J. C. Reichert, J. T. Schantz, U. Gbureck, L. Rackwitz, U. Nöth, F. Jakob, M. Rudert, J. Groll, D. W. Huttmacher, How smart do biomaterials need to be? A translational science and clinical point of view, *Advanced Drug Delivery Reviews*, 2013, **65**, 581-603, doi: 10.1016/j.addr.2012.07.009.
- [4] N. K. Chaudhari, H. Jin, B. Kim, D. San Baek, S. H. Joo, K. Lee, MXene: an emerging two-dimensional material for future energy conversion and storage applications, *Journal of Materials Chemistry A*, 2017, **5**, 24564-24579, doi: 10.1039/C7TA09094C.
- [5] Z. Li, N. H. Attanayake, J. L. Blackburn, E. M. Miller, Carbon dioxide and nitrogen reduction reactions using 2D transition metal dichalcogenide (TMDC) and carbide/nitride (MXene) catalysts, *Energy & Environmental Science*, 2021, **14**, 6242-6286, doi: 10.1039/D1EE03211A.
- [6] S. K. Hwang, S. M. Kang, M. Rethinasabapathy, C. Roh, Y. S. Huh, MXene: an emerging two-dimensional layered material for removal of radioactive pollutants, *Chemical Engineering Journal*, 2020, **397**, 125428, doi: 10.1016/j.cej.2020.125428.
- [7] M. Sun, S. Chu, Z. Sun, X. Jiao, L. Wang, Z. Li, L. Jiang, A review of etching methods and applications of two-dimensional MXenes, *Nanotechnology*, 2024, **35**, 382003, doi: 10.1088/1361-6528/ad53d0.
- [8] H. Huang, C. Dong, W. Feng, Y. Wang, B. Huang, Y. Chen, Biomedical engineering of two-dimensional MXenes, *Advanced Drug Delivery Reviews*, 2022, **184**, 114178, doi: 10.1016/j.addr.2022.114178.
- [9] A. Zamhuri, G. P. Lim, N. L. Ma, K. S. Tee, C. F. Soon, MXene in the lens of biomedical engineering: synthesis, applications and future outlook, *Biomedical Engineering Online*, 2021, **20**, 33, doi: 10.1186/s12938-021-00873-9.
- [10] A. Maleki, M. Ghomi, N. Nikfarjam, M. Akbari, E. Sharifi, M. A. Shahbazi, M. Kermanian, M. Seyedhamzeh, E. Nazarzadeh Zare, M. Mehrali, O. Moradi, F. Sefat, V. Mattoli, P. Makvandi, Y. Chen, Biomedical applications of MXene-integrated composites: regenerative medicine, infection therapy, cancer treatment, and biosensing, *Advanced Functional Materials*, 2022, **32**, 2203430, doi: 10.1002/adfm.202203430.
- [11] L. Chen, X. Dai, W. Feng, Y. Chen, Biomedical applications of MXenes: from nanomedicine to biomaterials, *Accounts of Materials Research*, 2022, **3**, 785-798, doi: 10.1021/accountsmr.2c00025.
- [12] X. Li, S. Wang, M. Zheng, Z. Ma, Y. Chen, L. Deng, W. Xu, G. Fan, S. Khademolqorani, S. N. Banitaba, A. I. Osman, Synergistic integration of MXene nanostructures into electrospun fibers for advanced biomedical engineering applications, *Nanoscale Horizons*, 2024, **9**, 1703-1724, doi: 10.1039/D4NH00209A.
- [13] S. Iravani, R. S. Varma, MXenes and MXene-based materials for tissue engineering and regenerative medicine: recent advances, *Materials Advances*, 2021, **2**, 2906-2917, doi: 10.1039/D1MA00189B.
- [14] B. Gürbüz, F. Ciftci, Bio-electric-electronics and tissue engineering applications of MXenes wearable materials: a review, *Chemical Engineering Journal*, 2024, **489**, 151230, doi: 10.1016/j.cej.2024.151230.
- [15] S. Iravani, R. S. Varma, MXenes for cancer therapy and diagnosis: recent advances and current challenges, *ACS Biomaterials Science & Engineering*, 2021, **7**, 1900-1913, doi: 10.1021/acsbomaterials.0c01763.
- [16] A. Szuplewska, D. Kulpińska, A. Dybko, M. Chudy, A. M.

- Jastrzębska, A. Olszyna, Z. Brzózka, Future applications of MXenes in biotechnology, nanomedicine, and sensors, *Trends in Biotechnology*, 2020, **38**, 264-279, doi: 10.1016/j.tibtech.2019.09.001.
- [17] I. C. Lee, Y. C. E. Li, J. L. Thomas, M. H. Lee, H. Y. Lin, Recent advances using MXenes in biomedical applications, *Materials Horizons*, 2024, **11**, 876-902, doi: 10.1039/D3MH01588B.
- [18] J. Huang, Z. Li, Y. Mao, Z. Li, Progress and biomedical applications of MXenes, *Nano Select*, 2021, **2**, 1480-1508, doi: 10.1002/nano.202000309.
- [19] A. Koyappayil, S. G. Chavan, Y. G. Roh, M. H. Lee, Advances of MXenes; perspectives on biomedical research, *Biosensors*, 2022, **12**, 454, doi: 10.3390/bios12070454.
- [20] M. Soleymaniha, M. A. Shahbazi, A. R. Rafieerad, A. Maleki, A. Amiri, Promoting role of MXene nanosheets in biomedical sciences: therapeutic and biosensing innovations, *Advanced Healthcare Materials*, 2019, **8**, 1801137, doi: 10.1002/adhm.201801137.
- [21] H. Li, R. Fan, B. Zou, J. Yan, Q. Shi, G. Guo, Roles of MXenes in biomedical applications: recent developments and prospects, *Journal of Nanobiotechnology*, 2023, **21**, 73, doi: 10.1186/s12951-023-01809-2.
- [22] I. C. Lee, Y. C. E. Li, J. L. Thomas, M. H. Lee, H. Y. Lin, Recent advances using MXenes in biomedical applications. *Materials Horizons*, 2024, **11**, 876-902, doi.org/10.1039/D3MH01588B.
- [23] H. Huang, R. Jiang, Y. Feng, H. Ouyang, N. Zhou, X. Zhang, Y. Wei, Recent development and prospects of surface modification and biomedical applications of MXenes, *Nanoscale*, 2020, **12**, 1325-1338, doi: 10.1039/C9NR07616F.
- [24] H. Lin, Y. Chen, J. Shi, Insights into 2D MXenes for versatile biomedical applications: current advances and challenges ahead, *Advanced Science*, 2018, **5**, 1800518, doi: 10.1002/advs.201800518.
- [25] K. Huang, Z. Li, J. Lin, G. Han, P. Huang, Two-dimensional transition metal carbides and nitrides (MXenes) for biomedical applications, *Chemical Society Reviews*, 2018, **47**, 5109-5124, doi: 10.1039/C7CS00838D.
- [26] R. Garg, F. Vitale, Latest advances on MXenes in biomedical research and health care, *Materials Research Society Bulletin*, 2023, **48**, 283-290, doi: 10.1557/s43577-023-00480-0.
- [27] A. M. Amani, L. Tayebi, E. Vafa, A. Jahanbin, M. Abbasi, A. Vaez, H. Kamyab, S. Chelliapan, Innovation applications of MXenes in biomedicine, *Materials Today Communications*, 2024, **40**, 109929, doi: 10.1016/j.mtcomm.2024.109929.
- [28] S. Iravani, E. Nazarzadeh Zare, P. Makvandi, Multifunctional MXene-based platforms for soft and bone tissue regeneration and engineering, *ACS Biomaterials Science & Engineering*, 2024, **10**, 1892-1909, doi: 10.1021/acsbiomaterials.3c01770.
- [29] B. Lu, Z. Zhu, B. Ma, W. Wang, R. Zhu, J. Zhang, 2D MXene nanomaterials for versatile biomedical applications: current trends and future prospects, *Small*, 2021, **17**, 2100946, doi: 10.1002/sml.202100946.
- [30] A. Zarepour, Ç. Karasu, Y. Mir, M. H. Nematollahi, S. Iravani, A. Zarrabi, Graphene- and MXene-based materials for neuroscience: diagnostic and therapeutic applications, *Biomaterials Science*, 2023, **11**, 6687-6710, doi: 10.1039/D3BM01114C.
- [31] S. M. George, B. Kandasubramanian, Advancements in MXene-polymer composites for various biomedical applications, *Ceramics International*, 2020, **46**, 8522-8535, doi: 10.1016/j.ceramint.2019.12.257.
- [32] F. Damiri, M. H. Rahman, M. Zehravi, A. A. Awaji, M. Z. Nasrullah, H. A. Gad, M. Z. Bani-Fwaz, R. S. Varma, M. O. Germoush, H. S. Al-malky, A. A. Sayed, S. Rojekar, M. M. Abdel-Daim, M. Berrada, MXene (Ti₃C₂T_x)-embedded nanocomposite hydrogels for biomedical applications: a review, *Materials*, 2022, **15**, 1666, doi: 10.3390/ma15051666.
- [33] N. Rabiee, S. Iravani, MXenes and their composites: a versatile platform for biomedical applications, *Materials Chemistry Horizons*, 2023, **2**, 171-184, doi: 10.22128/mch.2023.697.1043.
- [34] G. Basara, M. Saeidi-Javash, X. Ren, G. Bahcecioglu, B. C. Wyatt, B. Anasori, Y. Zhang, P. Zorlutuna, Electrically conductive 3D printed Ti₃C₂T_x MXene-PEG composite constructs for cardiac tissue engineering, *Acta Biomaterialia*, 2022, **139**, 179-189, doi: 10.1016/j.actbio.2020.12.033.
- [35] S. Iravani, R. S. Varma, MXenes in photomedicine: advances and prospects, *Chemical Communications*, 2022, **58**, 7336-7350, doi: 10.1039/D2CC01694J.
- [36] S. A. Kabli, M. Rafiq, I. Hamid, A. H. Rather, R. S. Khan, A. Abdal-hay, R. Hamid, H. A. Khan, R. M. Tripathi, S. Majeed, F. A. Sheikh, 3D printing with MXenes for next-generation implantable devices and tissue engineering applications, *Advanced Materials Technologies*, 2025, **251**, 2402017, doi: 10.1002/admt.202402017.
- [37] X. Lin, Z. Li, J. Qiu, Q. Wang, J. Wang, H. Zhang, T. Chen, Fascinating MXene nanomaterials: emerging opportunities in the biomedical field, *Biomaterials Science*, 2021, **9**, 5437-5471, doi: 10.1039/D1BM00526J.
- [38] V. G. Gayathri, B. Richard, J. T. Chacko, J. Bayry, P. A. Rasheed, Non-Ti MXenes: new biocompatible and biodegradable candidates for biomedical applications, *Journal of Materials Chemistry B*, 2025, **13**, 1212-1228, doi: 10.1039/D4TB01904K.
- [39] E. Mostafavi, S. Iravani, MXene-graphene composites: a perspective on biomedical potentials, *Nano-Micro Letters*, 2022,

- 14, 130, doi: 10.1007/s40820-022-00880-y.
- [40] N. Driscoll, B. Erickson, B. B. Murphy, A. G. Richardson, G. Robbins, N. V. Apollo, G. Mentzelopoulos, T. Mathis, K. Hantanasirisakul, P. Bagga, S. E. Gullbrand, M. Sergison, R. Reddy, J. A. Wolf, H. I. Chen, T. H. Lucas, T. R. Dillingham, K. A. Davis, Y. Gogotsi, J. D. Medaglia, F. Vitale, MXene-infused bioelectronic interfaces for multiscale electrophysiology and stimulation, *Science Translational Medicine*, 2021, **13**, eabf8629, doi: 10.1126/scitranslmed.abf8629.
- [41] M. Ramezani Farani, B. Nourmohammadi Khirak, R. Tao, Z. Wang, S. Ahmadi, M. Hassanpour, M. Rabiee, M. R. Saeb, E. C. Lima, N. Rabiee, 2D MXene nanocomposites: electrochemical and biomedical applications, *Environmental Science: Nano*, 2022, **9**, 4038-4068, doi: 10.1039/D2EN00527A.
- [42] A. Hamzehlouy, S. Zarei, R. Salah Othman, F. Shahi, H. Afshar, A. Afshar Taromi, H. A. Khonakdar, Recent advances in biomedical applications of MXene-integrated electrospun fibers: a review, *Polymer Advanced Technologies*, 2025, **36**, e70112, doi: 10.1002/pat.70112.
- [43] S. Selvaraj, A. Chauhan, R. Verma, K. Viswanathan, R. Subbarayan, S. Ghotekar, Multifunctional biomedical applications of MXene-based hydrogels: a review, *Inorganic Chemistry Communications*, 2024, **164**, 112457, doi: 10.1016/j.inoche.2024.112457.
- [44] I. A. Vasyukova, O. V. Zakharova, D. V. Kuznetsov, A. A. Gusev, Synthesis, toxicity assessment, environmental and biomedical applications of MXenes: a review, *Nanomaterials*, 2022, **12**, 1797, doi: 10.3390/nano12111797.
- [45] A. Hamzehlouy, M. Tavakoli Dare, F. Shahi, E. A. Dawi, H. A. Khonakdar, Recent advances in potential biomedical applications of MXene-based hydrogels, *Polymer Advanced Technologies*, 2024, **35**, e70008, doi: 10.1002/pat.70008.
- [46] A. Saxena, A. Tyagi, S. Vats, I. Gupta, A. Gupta, R. Kaur, S. K. Tiwary, A. A. Elzatahry, M. Singh, A. Karim, MXene-integrated composites for biomedical applications: synthesis, cancer diagnosis, and emerging frontiers, *Small Science*, 2025, **5**, 2400492, doi: 10.1002/smsc.202400492.
- [47] Y. O. Waidi, N. Jain, Unlocking new possibilities: application of MXenes in 3D bioprinting for advanced therapy, *Nanoscale*, 2024, **16**, 20037-20047, doi: 10.1039/D4NR02906B.
- [48] G. P. Lim, C. F. Soon, N. L. Ma, M. Morsin, N. Nayan, M. K. Ahmad, K. S. Tee, Cytotoxicity of MXene-based nanomaterials for biomedical applications: a mini review, *Environmental Research*, 2021, **201**, 111592, doi: 10.1016/j.envres.2021.111592.
- [49] A. VahidMohammadi, J. Rosen, Y. Gogotsi, The world of two-dimensional carbides and nitrides (MXenes), *Science*, 2021, **372**, eabf1581, doi: 10.1126/science.abf1581.
- [50] J. Wang, Y. Liu, Z. Cheng, Z. Xie, L. Yin, W. Wang, Y. Song, H. Zhang, Y. Wang, Z. Fan, Highly conductive MXene film actuator based on moisture gradients, *Angewandte Chemie International Edition*, 2020, **59**, 14029-14033, doi: 10.1002/anie.202003737.
- [51] J. Wang, H. Kang, H. Ma, Y. Liu, Z. Xie, Y. Wang, Z. Fan, Super-fast fabrication of MXene film through a combination of ion induced gelation and vacuum-assisted filtration, *Engineered Science*, 2021, **15**, 57-66, doi: 10.30919/es8d446.
- [52] S. K. Avinashi, R. K. Mishra, R. Singh, Shweta, Rakhi, Z. Fatima, C. R. Gautam, Fabrication methods, structural, surface morphology and biomedical applications of MXene: a review, *ACS Applied Materials & Interfaces*, 2024, **16**, 47003-47049, doi: 10.1021/acsami.4c07894.
- [53] M. Qin, C. Merzougui, Y. M. Su, Y. F. Li, W. Y. Chen, D. Huang, Recent developments in MXene and MXene/carbon composites for use in biomedical applications, *New Carbon Materials*, 2023, **38**, 496-506, doi: 10.1016/S1872-5805(23)60730-9.
- [54] Z. Li, H. Zhang, J. Han, Y. Chen, H. Lin, T. Yang, Surface nanopore engineering of 2D MXenes for targeted and synergistic multitherapies of hepatocellular carcinoma, *Advanced Materials*, 2018, **30**, 1706981, doi: 10.1002/adma.201706981.
- [55] S. Kumar, Fluorine-free MXenes: recent advances, synthesis strategies, and mechanisms, *Small*, 2024, **20**, 2308225, doi: 10.1002/smll.202308225.
- [56] M. Naguib, M. Kurtoglu, V. Presser, J. Lu, J. Niu, M. Heon, L. Hultman, Y. Gogotsi, M. W. Barsoum, Two-dimensional nanocrystals produced by exfoliation of Ti_3AlC_2 , *Advanced Materials*, 2011, **23**, 4248-4253, doi: 10.1002/adma.201102306.
- [57] M. Anayee, C. E. Shuck, M. Shekhirev, A. Goad, R. Wang, Y. Gogotsi, Kinetics of Ti_3AlC_2 etching for $Ti_3C_2T_x$ MXene synthesis, *Chemistry of Materials*, 2022, **34**, 9589-9600, doi: 10.1021/acs.chemmater.2c02194.
- [58] Q. Wei, H. Deng, H. Cui, J. Fang, Z. Zuo, J. Deng, Y. Li, X. Wang, L. Zhao, A mini review of fluoride-induced apoptotic pathways, *Environmental Science and Pollution Research*, 2018, **25**, 33926-33935, doi: 10.1007/s11356-018-3406-z.
- [59] S. Yang, P. Zhang, F. Wang, A. G. Ricciardulli, M. R. Lohe, P. W. M. Blom, X. Feng, Fluoride-free synthesis of two-dimensional titanium carbide (MXene) using a binary aqueous system, *Angewandte Chemie International Edition*, 2018, **57**, 15491-15495, doi: 10.1002/anie.201809662.
- [60] Y. Li, H. Shao, Z. Lin, J. Lu, L. Liu, B. Duployer, P. O. Å. Persson, P. Eklund, L. Hultman, M. Li, K. Chen, X.-H. Zha, S. Du, P. Rozier, Z. Chai, E. Raymundo-Piñero, P. L. Taberna, P. Simon, Q. Huang, A general Lewis acidic etching route for preparing MXenes with enhanced electrochemical performance in non-aqueous electrolyte, *Nature Materials*, 2020, **19**, 894-899, doi: 10.1038/s41563-020-0657-0.

- [61] P. Iravani, S. Iravani, R. S. Varma, MXene-chitosan composites and their biomedical potentials, *Micromachines*, 2022, **13**, 1383, doi: 10.3390/mi13091383.
- [62] A. Rafieerad, G. L. Sequiera, W. Yan, P. Kaur, A. Amiri, S. Dhingra, Sweet-MXene hydrogel with mixed-dimensional components for biomedical applications, *Journal of the Mechanical Behavior of Biomedical Materials*, 2020, **101**, 103440, doi: 10.1016/j.jmbbm.2019.103440.
- [63] Y. Cai, Y. Li, Y. Du, N. R. de Barros, P. R. Galligan, Z. Liu, Y. Li, H. Wong, K. Zhang, S. Khoseavi, N. H. Kouchehbaghi, Y. Zhu, Z. Luo, Three-dimensional assembled MXene architectures in biomedical innovations, *Chemistry of Materials*, 2024, **36**, 9234-9258, doi: 10.1021/acs.chemmater.4c00966.
- [64] A. Kamal, B. Li, S. Luo, I. Kinloch, L. Zheng, K. Liao, Engineering the mechanical properties of $Ti_3C_2T_x$ MXene films via thermal annealing treatment, *Nano Materials Science*, 2025, 1-11, doi: 10.1016/j.nanoms.2025.03.006.
- [65] R. Li, L. Zhang, L. Shi, P. Wang, MXene Ti_3C_2 : an effective 2D light-to-heat conversion material, *ACS Nano*, 2017, **11**, 3752-3759, doi: 10.1021/acsnano.6b08415.
- [66] S. Li, L. Ma, M. Zhou, Y. Li, Y. Xia, X. Fan, C. Cheng, H. Luo, New opportunities for emerging 2D materials in bioelectronics and biosensors, *Current Opinion in Biomedical Engineering*, 2020, **13**, 32-41, doi: 10.1016/j.cobme.2019.08.016.
- [67] A. K. Manoharan, M. I. K. Batcha, S. Mahalingam, B. Raj, J. Kim, Recent advances in two-dimensional nanomaterials for healthcare monitoring, *ACS Sensors*, 2024, **9**, 1706-1734, doi: 10.1021/acssensors.4c00015.
- [68] Y. Jiao, M. Lei, J. Zhu, R. Chang, X. Qu, Advances in electrode interface materials and modification technologies for brain-computer interfaces, *Biomaterials Translational*, 2023, **4**, 213, doi: 10.12336/biomatertransl.2023.04.003.
- [69] J. Liu, S. Li, S. Li, J. Tian, H. Li, Z. Pan, L. Lu, Y. Mao, Recent advances in natural-polymer-based hydrogels for body movement and biomedical monitoring, *Biosensors*, 2024, **14**, 415, doi: 10.3390/bios14090415.
- [70] L. Liu, D. Wang, Y. Luo, Y. Liu, Y. Guo, G. Yang, G. Qiu, Intraoperative assessment of microimplantation-induced acute brain inflammation with titanium oxynitride-based plasmonic biosensor, *Biosensors and Bioelectronics*, 2024, **264**, 116664, doi: 10.1016/j.bios.2024.116664.
- [71] J. Luo, C. Sun, B. Chang, Y. Jing, K. Li, Y. Li, Q. Zhang, H. Wang, C. Hou, MXene-enabled self-adaptive hydrogel interface for active electroencephalogram interactions. *ACS Nano*, 2022, **16**, 19373-19384, doi: 10.1021/acsnano.2c08961.
- [72] Y. Bian, H. Shi, Q. Yuan, Y. Zhu, Z. Lin, L. Zhuang, X. Han, P. Wang, M. Chen, X. Wang, Patterning techniques based on metallized electrospun nanofibers for advanced stretchable electronics, *Advanced Science*, 2024, **11**, 2309735, doi: 10.1002/advs.202309735.
- [73] C. B. Álvarez, A. Etxeberria, Y. Polo, J. R. Sarasua, E. Zuza, A. Larrañaga, Lactide and ethylene brassylate-based thermoplastic elastomers and their nanocomposites with carbon nanotubes: synthesis, mechanical properties and interaction with astrocytes, *Polymers*, 2022, **14**, 4656, doi: 10.3390/polym14214656.
- [74] Z. Lin, H. Shao, K. Xu, P. L. Taberna, P. Simon, MXenes as high-rate electrodes for energy storage, *Trends in Chemistry*, 2020, **2**, 654-664, doi: 10.1016/j.trechm.2020.04.010.
- [75] J. Wang, Y. Liu, Y. Yang, J. Wang, H. Kang, H. Yang, D. Zhang, Z. Cheng, Z. Xie, H. Tan, Z. Fan, A weldable MXene film assisted by water, *Matter*, 2022, **5**, 1042-1055, doi: 10.1016/j.matt.2022.01.014.
- [76] J. Wang, S. Zhang, J. Ma, X. Liu, Y. Ma, Z. Fan, J. Wang, Augmenting levoglucosan production through catalytic pyrolysis of biomass exploiting $Ti_3C_2T_x$ MXene, *Chinese Chemical Letters*, 2024, **35**, 109725, doi: 10.1016/j.cclet.2024.109725.
- [77] J. Wang, J. He, D. Kan, K. Chen, M. Song, W. Huo, MXene film prepared by vacuum-assisted filtration: properties and applications, *Crystals*, 2022, **12**, 1034, doi: 10.3390/cryst12081034.
- [78] H. Ma, J. Wang, J. Wang, K. Shang, Y. Yang, Z. Fan, Blade-coated $Ti_3C_2T_x$ MXene films for pseudocapacitive energy storage and infrared stealth, *Diamond and Related Materials*, 2023, **131**, 109587, doi: 10.1016/j.diamond.2022.109587.
- [79] J. Wang, H. Ma, Y. Liu, Z. Xie, Z. Fan, MXene-based humidity-responsive actuators: preparation and properties, *ChemPlusChem*, 2021, **86**, 406-417, doi: 10.1002/cplu.202000828.
- [80] F. Mohajer, G. M. Ziarani, A. Badiei, S. Iravani, R. S. Varma, Advanced MXene-based micro- and nanosystems for targeted drug delivery in cancer therapy, *Micromachines*, 2022, **13**, 1773, doi: 10.3390/mi13101773.
- [81] S. Iravani, A. Zarepour, A. Khosravi, R. S. Varma, A. Zarrabi, Smart MXene-based microrobots for targeted drug delivery and synergistic therapies, *Nanoscale*, 2025, **17**, 9040-9056, doi: 10.1039/D4NR05160B.
- [82] X. Han, J. Huang, H. Lin, Z. Wang, P. Li, Y. Chen, 2D ultrathin MXene-based drug-delivery nanoplatfor for synergistic photothermal ablation and chemotherapy of cancer, *Advanced Healthcare Materials*, 2018, **7**, 1701394, doi: 10.1002/adhm.201701394.
- [83] S. Kulkarni, S. Soman, P. D. Navti, A. A. Roy, A. N. Nikam, P. Vineeth, J. Kulkarni, K. S. Shirur, A. Pandey, S. D. George, S. Mutalik, Nano-innovations in cancer therapy: the unparalleled potential of MXene conjugates, *Materials*, 2024, **17**, 1423, doi: 10.3390/ma17061423.
- [84] G. Jamalipour Soufi, I. Parisa, H. Ali, M. Ebrahim, K.

- Mehrdad, S. and Iravani, MXenes and MXene-based materials with cancer diagnostic applications: challenges and opportunities, *Comments On Inorganic Chemistry*, 2022, **42**, 174-207, doi: 10.1080/02603594.2021.1990890.
- [85] S. Iravani, R. S. Varma, MXenes in cancer nanotheranostics, *Nanomaterials*, 2022, **12**, 3360, doi: 10.3390/nano12193360.
- [86] S. B. Lee, J. M. Park, R. Park, H. E. Choi, S. W. Hong, K. S. Kim, Synergistic chemo-photothermal treatment via MXene-encapsulated nanoparticles for targeted melanoma therapy, *Journal of Controlled Release*, 2025, **382**, 113729, doi: 10.1016/j.jconrel.2025.113729.
- [87] G. Perini, A. Rosenkranz, G. Friggeri, D. Zambrano, E. Rosa, A. Augello, V. Palmieri, M. De Spirito, M. Papi, Advanced usage of $Ti_3C_2T_x$ MXenes for photothermal therapy on different 3D breast cancer models, *Biomedicine & Pharmacotherapy*, 2022, **153**, 113496, doi: 10.1016/j.biopha.2022.113496.
- [88] N. Li, Y. Wang, Y. Li, C. Zhang, G. Fang, Recent advances in photothermal therapy at near-infrared-II based on 2D MXenes, *Small*, 2024, **20**, 2305645, doi: 10.1002/smll.202305645.
- [89] S. Lee, S. Kim, E.-S. Yu, S. Lee, M. J. Ko, H. Lee, D. H. Kim, Electric pulse regulated MXene based nanozymes for integrative bioelectricity immuno-cancer therapy, *Advanced Functional Materials*, 2025, 2420870, doi: 10.1002/adfm.202420870.
- [90] H. Zhu, Z. Zhang, R. Jiang, L. Xu, X. Yang, J. Chen, Z. Wang, X. Xu, Z. Liu, MXene-based nanosheet for enhanced glioma therapy via photonic hyperthermia to boost the abscopal effect of radioimmunotherapy, *Journal of Nanobiotechnology*, 2025, **23**, 203, doi: 10.1186/s12951-025-03288-z.
- [91] M. Tang, Y. Shi, L. Lu, J. Li, Z. Zhang, J. Ni, W. Wang, Y. Zhang, T. Sun, Z. Wu, Dual active nanozyme-loaded MXene enables hyperthermia-enhanced tumor nanocatalytic therapy, *Chemical Engineering Journal*, 2022, **449**, 137847, doi: 10.1016/j.cej.2022.137847.
- [92] Y. Luo, M. Chen, T. Zhang, Q. Peng, 2D nanomaterials-based delivery systems and their potentials in anticancer synergistic photo-immunotherapy, *Colloids and Surfaces B: Biointerfaces*, 2024, **242**, 114074, doi: 10.1016/j.colsurfb.2024.114074.
- [93] S. M. Mousavi, M. Y. Kalashgrani, M. Binazadeh, Y. Mazaheri, N. Omidifar, V. Rahmani, M. Riazi, C. W. Lai, R. H. Althomali, M. M. Rahman, A. Gholami, W. H. Chiang, Recent advancements in smart MXene quantum dot-based nanosystems for immunomodulatory and effective cancer treatment, *Materials Today Chemistry*, 2024, **38**, 102097, doi: 10.1016/j.mtchem.2024.102097.
- [94] J. Ma, L. Zhang, B. Lei, Multifunctional MXene-based bioactive materials for integrated regeneration therapy, *ACS Nano*, 2023, **17**, 19526-19549, doi: 10.1021/acsnano.3c01913.
- [95] A. Sinha, Dhanjai, H. Zhao, Y. Huang, X. Lu, J. Chen, R. Jain, MXene: an emerging material for sensing and biosensing, *TrAC-Trends in Analytical Chemistry*, 2018, **105**, 424-435, doi: 10.1016/j.trac.2018.05.021.
- [96] B. Xu, C. Zhi, P. Shi, Latest advances in MXene biosensors, *Journal of Physics: Materials*, 2020, **3**, 031001, doi: 10.1088/2515-7639/ab8f78.
- [97] A. Ali, S. M. Majhi, L. A. Siddig, A. H. Deshmukh, H. Wen, N. N. Qamhieh, Y. E. Greish, S. T. Mahmoud, Recent advancements in MXene-based biosensors for health and environmental applications-a review, *Biosensors*, 2024, **14**, 497, doi: 10.3390/bios14100497.
- [98] Y. Tao, K. Yi, H. Wang, H. W. Kim, K. Li, X. Zhu, M. Li, CRISPR-Cas12a-regulated DNA adsorption and metallization on MXenes as enhanced enzyme mimics for sensitive colorimetric detection of hepatitis B virus DNA, *Journal of Colloid and Interface Science*, 2022, **613**, 406-414, doi: 10.1016/j.jcis.2022.01.038.
- [99] W. Wang, H. Zhou, Z. Xu, Z. Li, L. Zhang, P. Wan, Flexible conformally bioadhesive MXene hydrogel electronics for machine learning-facilitated human-interactive sensing, *Advanced Materials*, 2024, **36**, 2401035, doi: 10.1002/adma.202401035.
- [100] M. Safarkhani, B. Farasati Far, E. C. Lima, S. Jafarzadeh, P. Makvandi, R. S. Varma, Y. Huh, M. Ebrahimi Warkiani, N. Rabiee, Integration of MXene and microfluidics: a perspective, *ACS Biomaterials Science & Engineering*, 2024, **10**, 657-676, doi: 10.1021/acsbmaterials.3c01361.
- [101] S. Radhakrishnan, M. Mathew, C. S. Rout, Microfluidic sensors based on two-dimensional materials for chemical and biological assessments, *Materials Advances*, 2022, **3**, 1874-1904, doi: 10.1039/D1MA00929J.
- [102] K. R. Khondakar, D. Tripathi, H. Mazumdar, K. Ahuja, A. Kaushik, Tailored MXenes and graphene as efficient telemedicine platforms for personalized health wellness, *Materials Advances*, 2024, **5**, 4091-4111, doi: 10.1039/D4MA00234B.
- [103] N. Li, J. Peng, W. J. Ong, T. Ma, Arramel, P. Zhang, J. Jiang, X. Yuan, C. Zhang, MXenes: an emerging platform for wearable electronics and looking beyond, *Matter*, 2021, **4**, 377-407, doi: 10.1016/j.matt.2020.10.024.
- [104] B. Fu, J. Sun, C. Wang, C. Shang, L. Xu, J. Li, H. Zhang, MXenes: synthesis, optical properties, and applications in ultrafast photonics, *Small*, 2021, **17**, 2006054, doi: 10.1002/smll.202006054.
- [105] H. Riazi, S. K. Nemani, M. C. Grady, B. Anasori, M. Soroush, Ti_3C_2 MXene-polymer nanocomposites and their applications, *Journal of Materials Chemistry A*, 2021, **9**, 8051-8098, doi: 10.1039/D0TA08023C.

- [106] Y. Chen, W. Liu, S. Wan, H. Wang, Y. Chen, H. Zhao, C. Zhang, K. Liu, T. Zhou, L. Jiang, Q. Cheng, X. Deng, Superior synergistic osteogenesis of MXene-based hydrogel through supersensitive drug release at mild heat, *Advanced Functional Materials*, 2024, **34**, 2309191, doi: 10.1002/adfm.202309191.
- [107] B. Zhang, H. Zhang, Y. Hu, L. Tian, H. Cheng, Y. Wang, X. Gao, Q. Cui, S. Zheng, P. Feng, F. Bian, Y. Wang, T. Liu, C. Zhang, R. Chai, Decellularized umbilical cord wrapped with conductive hydrogel for peripheral nerve regeneration, *Aggregate*, 2025, **6**, 674, doi: 10.1002/agt2.674.
- [108] B. Farasati Far, N. Rabiee, S. Iravani, Environmental implications of metal-organic frameworks and MXenes in biomedical applications: a perspective, *RSC Advances*, 2023, **13**, 34562-34575, doi: 10.1039/D3RA07092A.
- [109] Z. Cao, Y. Bian, T. Hu, Y. Yang, Z. Cui, T. Wang, S. Yang, X. Weng, R. Liang, C. Tan, Recent advances in two-dimensional nanomaterials for bone tissue engineering, *Journal of Materiomics*, 2023, **9**, 930-958, doi: 10.1016/j.jmat.2023.02.016.
- [110] A. A. Fadahunsi, C. Li, M. I. Khan, W. Ding, MXenes: state-of-the-art synthesis, composites and bioapplications, *Journal of Materials Chemistry B*, 2022, **10**, 4331-4345, doi: 10.1039/D2TB00289B.
- [111] S. Iravani, N. Rabiee, P. Makvandi, Advancements in MXene-based composites for electronic skins, *Journal of Materials Chemistry B*, 2024, **12**, 895-915, doi: 10.1039/D3TB02247A.
- [112] S. Balasamy, D. Ganapathy, R. Atchudan, S. Arya, A. K. Sundramoorthy, Chitosan/MXene composite scaffolds for bone regeneration in oral cancer treatment-a review, *Current Cancer Therapy Reviews*, 2025, **21**, e15733947326282, doi: 10.2174/0115733947326282240924003811.
- [113] K. Manibalan, J. T. Chen, Recent progress on MXene-polymer composites for soft electronics applications in sensing and biosensing: a review, *Journal of Materials Chemistry A*, 2024, **12**, 27130-27156, doi: 10.1039/D4TA04211E.
- [114] K. Nasrin, V. Sudharshan, K. Subramani, M. Sathish, Insights into 2D/2D MXene heterostructures for improved synergy in structure toward next-generation supercapacitors: a review, *Advanced Functional Materials*, 2022, **32**, 2110267, doi: 10.1002/adfm.202110267.
- [115] V. Ferrara, C. Perfili, G. Artemi, B. Iacolino, F. Sciandra, G. Perini, L. Fusco, M. Pogorielov, L. G. Delogu, M. Papi, M. De Spirito, V. Palmieri, Advanced approaches in skin wound healing-a review on the multifunctional properties of MXenes in therapy and sensing, *Nanoscale*, 2024, **16**, 18684-18714, doi: 10.1039/D4NR02843K.
- [116] X. He, S. Koo, E. Obeng, A. Sharma, J. Shen, J. S. Kim, Emerging 2D MXenes for antibacterial applications: current status, challenges, and prospects, *Coordination Chemistry Reviews*, 2023, **492**, 215275, doi: 10.1016/j.ccr.2023.215275.
- [117] F. Seidi, A. Arabi Shamsabadi, M. Dadashi Firouzjaei, M. Elliott, M. R. Saeb, Y. Huang, C. Li, H. Xiao, B. Anasori, MXenes antibacterial properties and applications: a review and perspective, *Small*, 2023, **19**, 2206716, doi: 10.1002/sml.202206716.
- [118] L. Nie, Q. Wei, J. Li, Y. Deng, X. He, X. Gao, X. Ma, S. Liu, Y. Sun, G. Jiang, O. V. Okoro, A. Shavandi, S. Jing, Fabrication and desired properties of conductive hydrogel dressings for wound healing, *RSC Advances*, 2023, **13**, 8502-8522, doi: 10.1039/D2RA07195A.
- [119] S. Khattak, I. Ullah, H. Xie, X. Tao, H. Xu, J. Shen, Self-healing hydrogels as injectable implants: advances in translational wound healing, *Coordination Chemistry Reviews*, 2024, **509**, 215790, doi: 10.1016/j.ccr.2024.215790.
- [120] Z. Li, Z. Chen, H. Chen, K. Chen, W. Tao, X. K. Ouyang, L. Mei, X. Zeng, Polyphenol-based hydrogels: pyramid evolution from crosslinked structures to biomedical applications and the reverse design, *Bioactive Materials*, 2022, **17**, 49-70, doi: 10.1016/j.bioactmat.2022.01.038.
- [121] Y. Li, R. Fu, Z. Duan, C. Zhu, D. Fan, Artificial nonenzymatic antioxidant MXene nanosheet-anchored injectable hydrogel as a mild photothermal-controlled oxygen release platform for diabetic wound healing, *ACS Nano*, 2022, **16**, 7486-7502, doi: 10.1021/acsnano.1c10575.
- [122] C. Yang, Y. Luo, H. Lin, M. Ge, J. Shi, X. Zhang, Niobium carbide MXene augmented medical implant elicits bacterial infection elimination and tissue regeneration, *ACS Nano*, 2021, **15**, 1086-1099, doi: 10.1021/acsnano.0c08045.
- [123] J. Sui, Y. Hou, M. Chen, Z. Zheng, X. Meng, L. Liu, S. Huo, S. Liu, H. Zhang, Nanomaterials for anti-infection in orthopedic implants: a review, *Coatings*, 2024, **14**, 254, doi: 10.3390/coatings14030254.
- [124] J. Fu, Y. Li, T. Zhou, S. Fang, M. Zhang, Y. Wang, K. Li, W. Lian, L. Wei, R. H. Baughman, Q. Cheng, Large stroke radially oriented MXene composite fiber tensile artificial muscles, *Science Advances*, 2025, **11**, eadt1560, doi: 10.1126/sciadv.adt1560.
- [125] S. Wang, Z. Zhang, R. Tang, F. He, Y. Huang, Z. Nie, C. Lei, Responsive MXene nanovehicles deliver CRISPR/Cas12a for boolean logic-controlled gene editing, *Science China Chemistry*, 2022, **65**, 2318-2326, doi: 10.1007/s11426-022-1376-1.
- [126] T. Liu, Q. Zheng, W. Cao, Y. Wang, M. Zhang, Q. Zhao, M. Cao, Dielectric genes editing MXene to switch electromagnetic functions, *Advanced Composites and Hybrid Materials*, 2024, **7**, 79, doi: 10.1007/s42114-024-00894-7.
- [127] M. Tavakolizadeh, M. Atarod, S. J. Seyyed Tabaei, S. Sojdedh, E. Nazarzadeh Zare, M. Rabiee, N. Rabiee, Green

modified-UiO-66/MXene sandwich composites for gene-chemotherapy synergistic cancer suppression: Co-delivery of doxorubicin and pCRISPR, *Alexandria Engineering Journal*, 2023, **80**, 144-154, doi: 10.1016/j.aej.2023.08.046.

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits the use, sharing, adaptation, distribution and reproduction in any medium or format, as long as appropriate credit to the original author(s) and the source is given by providing a link to the Creative Commons License and changes need to be indicated if there are any. The images or other third-party material in this article are included in the article's Creative Commons License, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons License 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 License, visit <http://creativecommons.org/licenses/by/4.0/>.

©The Author(s) 2025