Research Progress on MXene Composite Hydrogels in Biomedical Engineering

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Abstract: As a new type of 2D material, MXene has received extensive attention in recent years. With the excellent superior physical and chemical properties, including a substantial specific surface area and flexible and adaptable surface functional groups, MXene can be compounded with hydrogel to form MXene hydrogel. This article systematically reviews the recent progress of MXene hydrogels in medical diagnosis and treatment in latest years, and describes the basic properties of MXene and MXene hydrogels in related fields. The focus is on the cutting-edge applications of MXene-based hydrogels in four areas: drug delivery, photothermal therapy, biosensing, and tissue repair. At the same time, an overview of its limitations in various fields is given, focusing on the uncertainty of long-term safety in vivo, the lack of clinical trials, instability in the face of complex environments, and the low level of photothermal conversion efficiency. Finally, this article discusses the challenges and prospective applications of MXene-based hydrogels in practical contexts, addressing existing obstacles to unlock their capabilities in clinical and biomedical fields.

1 INTRODUCTION

Hydrogel is a kind of polymer material with a three-dimensional network structure. Due to its good water retention and biocompatibility, it also has broad application prospects in the biomedical field. However, traditional hydrogels have limitations such as low conductivity, poor mechanical properties, and slow response to external stimuli. In recent years, MXene, as an emerging 2D material, has been widely used to improve and modify the performance of hydrogels. Compared with other two-dimensional materials, MXene has excellent conductivity, mechanical properties, hydrophilicity, biocompatibility and other properties (Wang, Liang & Zhang, 2024; Ren et al., 2023). This not only makes up for the functional deficiencies of hydrogels but also gives them new functional properties, such as antibacterial properties, photothermal effects, etc., bringing new development opportunities for biomedical materials (He et al., 2025).

This article comprehensively discusses and summarizes the breakthrough progress of MXene hydrogels in related biomedical fields in the past five years and the challenges and opportunities that may be encountered in the future. It aims to provide a theoretical foundation and technological reference for the research and development of the upcoming generation of intelligent biomedical materials.

2 THE BASIC PROPERTIES OF MXENE AND MXENE HYDROGELS

MXene-based hydrogel is a novel kind of composite material that has garnered a lot of interest due to its distinct chemical and physical characteristics. It not only has excellent mechanical qualities, which can significantly improve hydrogel's toughness and strength , but also has good electrical conductivity, which makes it show tremendous promise in the domains of electronic devices and flexible sensors. In addition, the photothermal performance of MXene-based hydrogel is also very outstanding, which is suitable for photothermal therapy and the preparation of photothermal-driven materials. At the same time, its good biocompatibility and certain antibacterial properties give it broad application prospects in tissue engineering and drug carriers. These comprehensive properties make MXene-based hydrogels show

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strong competitiveness in many fields, providing a new direction for future biomedical research.

2.1 Mechanical Properties

Due to its abundant surface functional groups, MXene can cross-link with polymer chains to produce a special 3D network structure, thereby enhancing the mechanical properties of the material, including elastic and tensile modulus. Huang et al. (2025) prepared a polyvinyl alcohol (PVA) /$Zn(CF_3SO_3)_2$ hydrogel electrolyte loaded with MXene (MPZC), with a stretchability of up to 350% and the ability to withstand multiple twists. It can stretch up to 514% when broken. And after repairing the adhesion, the load-bearing capacity gradually recovers over time. The elongation at break of the hydrogel was 296% 3 hours after repair, and the compressive strength was 1032.192MPa at the maximum compressive strain of 79.089%, showing excellent self-healing ability. However, with the increase in the number of self-healing times, the impedance of the material increased slightly, and the original structure could not be fully restored. Despite this, MPZC hydrogel is still a strong and self-healing electrolyte. When MXenes are used as cross-linkers/nanofillers in hydrogels, they introduce new functionalities to hydrogels and enhance their inherent mechanical properties, such as surface adhesion, stretchability, self-healing ability, etc., making them suitable candidates for flexible wearable devices.

2.2 Conductivity

MXene's unique structure consists of a metal part and a carbide core, and the carbide core has a tremendous surface area and excellent ability to conduct, showing the characteristics of carbon-based materials. Lotfi et al. (2025) found that the addition of an appropriate amount of MXene nanosheets can enhance hydrogel's conductivity, with the highest conductivity reaching 975.4 ± 170.2μS/cm (0.125 mg/L concentration). However, when the MXene concentration is further increased, the conductivity will decrease due to the aggregation of nanosheets. In addition, Tran et al. (2020) demonstrated the thermal response regulation of the conductivity of mixed MXene by PDMAEMA functionalized MXene films, showing different conductivity changes according to the film, and applied its conductivity change characteristics with temperature to sensors. Therefore, the electrical properties of hydrogels can be improved by doping MXene, thereby promoting the accelerated development of artificial skin, sensors, etc.

2.3 Photothermal Property

MXene can absorb photons and release heat under the stimulation of near-infrared (NIR) light with excellent photothermal conversion efficiency and a wide absorption spectrum. The main causes of MXene's photothermal properties are the localized surface plasmon resonance (LSPR) effect and efficient redox (Lin et al., 2017). Xian et al. (2025) found the photothermal performance of ε-polylysine (EPL)/V2C MXene composites as photothermal transfer photocatalysts with a photothermal conversion efficiency at 21.4%. In three cycles of testing, the maximum temperature of the EPL/V2C composite suspension remained stable, indicating high photothermal stability. In addition, even at low concentrations, the temperature tended to stabilize and rise by about 40°C.

In another study, Cui et al. (2023) prepared MXene-Fe3O4-PNA (MFeP) composites, which showed outstanding photothermal conversion performance in both submerged environments and dry states. In addition, the temperature of the MFeP solution can increase quickly by nearly 15°C from 25°C in 20 seconds when 1.0 W/cm2 infrared light is used, with excellent photothermal conversion cycle stability as well. The wide-spectrum absorption characteristics of MXene give the hydrogel efficient photothermal conversion ability, which can quickly heat up under near-infrared light stimulation, and the good photothermal stability makes the MXene hydrogel highly recyclable, suitable for photothermal therapy or intelligent driving materials. However, the photothermal conversion efficiency has limited its application in the photothermal field to a certain extent.

2.4 Biocompatibility and Antibacterial Properties

MXene has a negatively charged hydrophilic surface, which also means that it has good biocompatibility. Meanwhile, MXene nanosheets can destroy the cell structure of bacteria because of their sharp edges and enrichment in reactive oxygen species, which can kill cancer cells and pathogens through redox reactions, thus having excellent antibacterial properties (He et al., 2025). Wang et al. (2025) dynamically crosslinked dopamine-modified chondroitin sulfate (ChS-DA) with SHP and MXene embedded phenylboronic acid (PBA) gelatin methacryloyl

(GelMA-PBA) to prepare GPC/MXene/SHP hydrogel. As evaluated by CCK8 and fluorescence staining experiments, GPC/MXene/SHP hydrogels containing 200μg/mL of MXene did not significantly alter cell viability when compared to the control group. Live/dead fluorescence images and actin skeleton staining further confirmed the healthy growth and proliferation of cells in the MXene-based hydrogel environment. Besides, in in vitro antibacterial experiments, both GPC/MXene and GPC/MXene/SHP showed good antibacterial properties.

Good biocompatibility and antibacterial properties allow MXene-based hydrogels to be used in in vivo treatment and wound healing. Nevertheless, the specific mechanism of cytotoxicity is not fully understood, and in specific cases, it is necessary to reduce its cytotoxicity by surface modification and adjusting the size of MXene.

3 APPLICATIONS IN THE BIOMEDICAL FIELD

3.1 Drug Delivery

Stimuli-responsive hydrogel systems show broad application prospects in the field of drug delivery. MXene hydrogels have in vitro cell compatibility and in vivo biosafety and can be used for in vivo treatment. At the same time, due to the sensitivity of responding to multiple external triggering factors, MXene composite hydrogels can not only achieve targeted drug delivery, but also accurately control drug dosage.

The combination of MXene and low-melting-point hydrogel materials is anticipated to create intelligent hydrogels with reversible phase transitions, which can regulate the medication delivery by controlling the heat that MXene releases(Dong et al., 2021; He et al., 2024). For example, He et al. (2024) prepared MXene@GG hydrogel by mixing gellan gum (GG), MXene nanosheets and FeCl2 solution, which is an ingenious drug delivery system that transfers doxorubicin (DOX). The MXene@GG hydrogel undergoes a sol-gel transition when exposed to 808nm NIR light, allowing for easy tuning of drug release kinetics. At the same time, MXene@GG hydrogels can withstand deformation and preserve structural integrity under large strains. MXene@GG hydrogels are cytocompatible and retain their anticancer properties even after the drug is released from the network after 880nm NIR irradiation.

What's more, Yang et al. (2022) synthesized an MXene hydrogel (MNPs@MXene) cross-linked with mixed Fe_3O_4@SiO_2 magnetic nanoparticles (MNPs) for loading silver nanoparticles (AgPNs). MNPS@MXene hydrogel can rapidly heat up under NIR light and alternating magnetic field (AMF) stimulation and has photothermal stability. Due to the expansion and contraction properties of the hydrogel and its rapid response to temperature, MNPS@MXene hydrogel can achieve rapid drug release, and only a small amount of AgNPs is released in the absence of external stimulation.

Although MXene-based hydrogels can achieve excellent performance in temporal and spatial control, the degradation kinetics and metabolic pathways of MXene nanosheets in vivo are not clear and the long-term in vivo safety has not been fully clarified. Its potential cytotoxicity, immunogenicity and accumulation of nanoparticles in organs may cause inflammation or chronic toxicity risks, which need to be further systematically evaluated.

3.2 Tissue Engineering

MXene hydrogels' biocompatibility and biodegradability make them useful for tissue restoration. At the same time, the excellent tissue adhesion and rheological properties of MXene hydrogels can fill irregular injured areas, which is conducive to cell migration and proliferation. The conductivity of MXene hydrogels also helps promote the regeneration of damaged tissue cells and provides a suitable microenvironment for cell regeneration.

Yu et al. (2023) mixed phytic acid (PA), polyvinyl pyrrolidone (PVP) and MXenes to prepare a new hydrogel (PPM) to cure traumatic spinal cord injury (SCI). Based on its liquid state at low frequency, PPM hydrogel is able to conform to the substrate's rough surface, which is conducive to the interaction between the interfaces. PPM hydrogel has excellent adhesion strength, which makes the hydrogel not easy to fall off during tissue deformation. Conducive to the transmission of bioelectric signals, a wider hysteresis loop and a much higher conductivity are reviewed in the experiment when compared with the control hydrogel without MXene (PP hydrogel (PA, PVP)). In the evaluation of spinal cord repair and regeneration pathology, PPM hydrogel is also more able to promote angiogenesis, myelin regeneration, axon regeneration, and calcium-dependent signaling protein production to achieve SCI recovery than PP hydrogel.

Wang et al. (2024) prepared a $Mo_2Ti_2C_3$ MXene hydrogel. In the experiment of the effect of $Mo_2Ti_2C_3$

MXene hydrogel on mouse bone regeneration, the MXene hydrogel had more new bone formation and higher bone mineral density than groups, one with only hydrogel and the other with none. By measuring the content of nerve growth factor NGF, osteogenic marker Runx2, neural factor BDNF and OCN, it was found that the experimental group had a larger number of any of the above cells than the hydrogel and control groups, reflecting the important role of $Mo_2Ti_2C_3$ MXene hydrogel in the secretion of nerve growth factor and bone regeneration.

Similar to drug delivery, the long-term safety of MXene in the human body applied in tissue engineering remains to be explored. In addition, present research is still being conducted in a lab, mainly focusing on in vitro experiments, cell experiments and low-level animal models, so clinical research has not been widely carried out. There is still a long way to go in the application of tissue engineering.

3.3 Biosensors

MXene hydrogels have great potential in smart wearable sensors due to their excellent self-healing ability and flexibility. Owing to their easy functionalization and high conductivity, MXene hydrogels are not only important in detecting in vitro physiological signals such as blood pressure and heart rate, but can also be used for in vivo disease monitoring and diagnosis.

Li et al. (2024) prepared a mixture of silk fibroin (SF)-modified MXene and polyacrylamide (MPS) hydrogels, which can successfully detect slight temperature changes through electrical signals. The sensor reacts quickly to temperature changes and has excellent recovery ability, and can be affixed to various regions of the body for real-time motion tracking. Liu et al. (2024) found that MPS hydrogels change resistance depending on the pressure. In addition, MPS hydrogels have excellent self-healing ability, and the resistivity is close to a stable state after being stretched 200 times at a tensile strain of 200%. Based on this, MPS hydrogels can be used as flexible strain sensors to track multiple human motion states in real time, for example, muscle twitching, throat swallowing, and pulse beating. Ryplida et al. (2023) made PTiM hydrogel based on TiO_2/MXene integrated polymer dots (PD-MX/TiO_2). Because cancer cells have a higher than normal H_2O_2 content, and the conductive and photothermal properties of the hydrogel after reacting with H_2O_2 change, PTiM hydrogel sensors can be used for early cancer diagnosis.

Although MXene hydrogels provide the possibility of multifunctional smart sensors, in some practical applications, they need to face complex environmental factors such as temperature changes and mechanical stress. One of the main concerns is how to make hydrogels more stable and dependable in these intricate settings.

3.4 Photothermal Therapy

Traditional PTT systems usually lack enough interactions to effectively attach bacteria and require indirect heat transfer pathways. This reduces the effectiveness of photothermal ablation and may burn normal tissues. MXene's superior photothermal qualities allow it to be applied to PPT for precise targeted treatment. The MXene@polyvinyl alcohol (PVA) gel prepared by Li et al. (2022) has excellent photothermal effect and photothermal conversion sensitivity. Based on the photothermal effect of MXene and the broad-spectrum antibacterial activity of hydrogels, MXene@PVA hydrogel can effectively curb bacterial proliferation and greatly promote wound healing, and may become useful in antibacterial wound healing dressing.

Hu et al. (2024) combined $Ti_3C_2T_x$ MXene with Zn^{2+} and doped it into sodium alginate (SA) and agar (AG) to make MSG-Zn^{2+} hydrogel. Among them, MXene enhances the swelling properties of the hydrogel and can better absorb wound exudate. At the same time, the introduction of Zn^{2+} enhances the electrostatic interaction with negative-charged bacteria, encourages the physical destruction of MXene on bacteria and reduces the heat transfer distance, improves the photothermal conversion efficiency, and reduces damage to surrounding tissues. In addition, Zn^{2+} can enhance the antibacterial activity of hydrogels and promote skin regeneration. This shows that MSG-Zn^{2+} hydrogels have great potential in wound treatment.

Although MXene-based hydrogels can achieve rapid heating, their efficiency still needs to be improved. How to further improve their photothermal conversion efficiency to achieve lower power density and higher therapeutic effect remains a challenge. In addition, the applicability of MXene-based hydrogels in deep tissue therapy is restricted since current research essentially ignores the investigation of the photothermal characteristics of MXene hydrogels at various depths.

4 CONCLUSION

MXene-based hydrogels have shown great application prospect in many biomedical fields including drug delivery, tissue engineering, biosensing and photothermal therapy in recent years. This article systematically reviews the breakthrough progress made by MXene-based hydrogels in medicine in the past five years and explores the challenges and opportunities that may be faced in future development. However, there is still room for improvement in the long-term biosafety and therapeutic effectiveness of MXene-based hydrogels. In addition, the preparation of MXene-based hydrogels with nanoscale pores still has deficiencies in stability and durability, which is not conducive to the long-term use of MXene hydrogels. MXene-based hydrogels also face some challenges in photothermal therapy, mainly focusing on the photothermal conversion efficiency and light penetration depth.

In the future, the research on MXene hydrogels can focus on optimizing the surface modification and functionalization of MXene to further improve its photothermal, antibacterial, antioxidant, and other properties, thereby enhancing the safety of hydrogels and extending their service life. In addition, the stability and durability of MXene-based hydrogels can be improved by optimizing the preparation process, such as introducing cross-linkers or using dynamic covalent bonding. It is hoped that the research results of this article can provide a solid theoretical foundation and clear technical path for the research and development of MXene-based hydrogels in the next generation of smart biomedical materials, and promote the development of this field.

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