MXene-Based Materials for Biomedical Applications: A Comprehensive Review

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Abstract

Two-dimensional materials have opened new possibilities in biomedical science due to their unique physicochemical properties and high surface-to-volume ratio. Among these, MXenes, a class of transition metal carbides and nitrides, have emerged as highly promising candidates for diverse biomedical applications. Their metallic conductivity, hydrophilic nature, and tunable surface chemistry enable efficient interaction with biological systems and facilitate functionalization with biomolecules, drugs, and polymers. This article presents a comprehensive overview of MXenes, focusing on their synthesis, structural characteristics, and key properties relevant to biomedical use. Special emphasis is placed on their applications in biosensing, diagnostic platforms, medical imaging, drug delivery, and cancer therapy. Additionally, their antimicrobial activity, role in wound healing, and potential in tissue engineering and implantable devices are critically discussed. Despite their promising performance, challenges related to stability, large-scale synthesis, and long-term Biocompatibility remains significant. The review highlights current advancements and outlines future research directions aimed at improving the safety, functionality, and clinical translation of MXene based biomedical systems.

Keywords: MXenes, biomedical applications, biosensors, photothermal therapy, tissue engineering, bioelectronics, medical imaging.

I. INTRODUCTION

Two-dimensional (2D) materials have attracted considerable attention in biomedical research due to their high surface area, tuneable surface chemistry, and unique electronic properties [1]. Among them, MXenes, a family of transition metal carbides, nitrides, and carbonitrides with the general formula $M_{n+1}X_nT_x$, have emerged as promising candidates for biomedical applications [2]. Here, M denotes an early transition metal such as titanium or niobium, X represents carbon and/or nitrogen, and T_x corresponds to surface functional groups such as –OH, –O, and –F generated during etching [3].

MXenes combine metallic conductivity with hydrophilicity and mechanical flexibility, making them highly compatible with biological systems [4]. Their layered structure and rich surface chemistry enable functionalization with drugs, biomolecules, and polymers, expanding their applicability in biosensing, imaging, therapy, and tissue engineering [5]. This review discusses the synthesis, properties, and biomedical applications of MXenes with emphasis on their role in diagnostics and therapy.

II. STRUCTURE AND SYNTHESIS OF MXENES

MXenes are commonly synthesized by selectively etching the A-layer from MAX phases using fluoride-containing etchants or electrochemical methods [3], [6]. The removal of the A-layer produces stacked MXene sheets that can be delaminated into single or few-layer nanosheets. These nanosheets possess a high aspect ratio and abundant surface functional groups that allow dispersion in water and interaction with biomolecules [4]. The surface terminations play a crucial role in determining the biocompatibility, stability, and chemical reactivity of MXenes [7]. Their large surface area provides multiple active sites for drug adsorption and biomolecule attachment, while their electrical conductivity makes them suitable for electrochemical biosensors and bioelectronic devices [8].

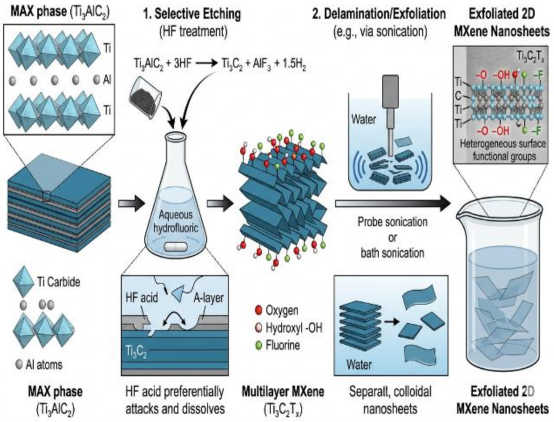

Fig 1. Schematic illustration of MXene synthesis from MAX phase by selective etching and exfoliation, producing layered 2D nanosheets with surface terminations (–O, –OH, –F).

III. MXENES IN BIOSENSING AND DIAGNOSTICS

MXene-based biosensors exploit their high conductivity and surface functionality for sensitive detection of biomolecules [8], [9]. Their negatively charged surfaces enable immobilization of enzymes, antibodies, and nucleic acids, making them suitable for electrochemical and optical sensing platforms [10]. Electrochemical MXene sensors have demonstrated excellent sensitivity toward glucose, hydrogen peroxide, dopamine, and cancer biomarkers [11]. In fluorescence-based systems, MXenes act as efficient quenchers and enable fluorescence resonance energy transfer (FRET)-based detection of DNA and microRNA [12]. Field-effect transistor

(FET) sensors fabricated using MXenes allow label-free and real-time monitoring of biological signals [13].

IV. IMAGING APPLICATIONS

MXenes possess strong absorption in the near-infrared (NIR) region, making them suitable for photoacoustic and photothermal imaging [14]. In addition, MXenes containing heavy elements such as tantalum or niobium provide excellent contrast for computed tomography (CT) imaging [15]. By modifying MXene surfaces with biocompatible polymers, prolonged blood circulation and targeted imaging can be achieved [16]. Their multifunctional nature allows integration of imaging and therapy within a single nanoplatform, enabling theranostic applications [17].

V. DRUG DELIVERY AND CANCER THERAPY

MXenes exhibit high drug loading capacity due to their layered structure and surface functional groups [18]. Drugs can be adsorbed through electrostatic interactions, hydrogen bonding, or π–π stacking. Stimuli-responsive MXene systems release drugs in response to pH changes or redox conditions in tumor microenvironments [19]. MXenes also show strong photothermal conversion efficiency, enabling photothermal therapy (PTT) [20]. Upon near-infrared laser irradiation, MXenes generate localized heat that destroys cancer cells. When combined with drug delivery or photodynamic therapy (PDT), synergistic therapeutic effects are achieved, enhancing treatment efficiency [21].

VI. ANTIMICROBIAL ACTIVITY AND WOUND HEALING

MXenes demonstrate intrinsic antibacterial activity due to their sharp edges, oxidative stress induction, and photothermal effects [22]. These properties make them useful in wound dressings and antibacterial coatings [23]. MXene-based wound dressings have been developed to prevent bacterial infection while simultaneously monitoring wound conditions through electrical signals [24]. Their ability to scavenge reactive oxygen species also contributes to reduced inflammation and accelerated tissue regeneration [25].

VII. TISSUE ENGINEERING AND IMPLANTABLE DEVICES

MXenes are increasingly explored in tissue engineering due to their mechanical strength and electrical conductivity [26]. When incorporated into hydrogels or polymer scaffolds, MXenes enhance cell adhesion, proliferation, and differentiation

[27]. Conductive MXene-based scaffolds enable electrical stimulation of nerve and muscle cells, improving tissue regeneration outcomes [28]. MXenes also serve as coatings for implants and electrodes, improving biocompatibility and signal transmission in bioelectronic devices [29].

VIII. BIOCOMPATIBILITY AND SAFETY CONSIDERATIONS

Although many studies report low cytotoxicity of MXenes at moderate concentrations, their long-term biocompatibility and biodegradation remain under investigation [30]. Surface modification strategies such as polymer coating and biomolecule functionalization significantly reduce toxicity and improve stability in physiological environments [31]. Comprehensive in vivo studies are required to evaluate biodistribution, clearance, and possible accumulation in organs before clinical translation [32].

IX. CHALLENGES AND FUTURE PERSPECTIVES

Key challenges in MXene biomedical applications include oxidation in aqueous media, limited large-scale synthesis, and incomplete understanding of long-term toxicity [33]. Future research should focus on developing stable, biodegradable MXenes and multifunctional systems that combine sensing, imaging, and therapy [34]. With advances in material engineering and biomedical integration, MXenes are expected to play a vital role in next-generation diagnostic and therapeutic technologies [35].

X. CONCLUSION

MXenes represent a versatile and powerful class of nanomaterials for biomedical applications. Their unique combination of conductivity, hydrophilicity, and surface tunability enables applications ranging from biosensing and imaging to drug delivery and tissue engineering. Although challenges remain in terms of safety and stability, continuous progress in MXene research is paving the way toward their use in advanced healthcare technologies [2], [35].

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