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MXene (Ti C Tx) based nanosheet photocatalysts for water remediation: challenges and recent developments

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HIGHLIGHTS

- MXene synthesis and applications in water treatment were explored.
- MXene's nanostructure and hydrophilicity showed promise for eco-friendly water treatment.
- MXene versatility shined in heavy metal, dye, radionuclide removal, and membrane and capacitive deionization uses.
- MXene faces challenges in safety, stability, toxicity, and practical application.
- MXene nano photocatalysts present an optimistic future for water remediation.

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ABSTRACT

Two-dimensional nano structural compounds are attracting the focus of researchers worldwide. The need to treat wastewater and prevent the release of hazardous substances into the environment has increased because of growing environmental awareness. New compounds, most of which are not biodegradable, have emerged due to rising consumer expectations. Due to their distinctive chemical and physical characteristics, MXene has lately been recognized as an exciting option. The strong hydrophilicity of MXene makes them a promising candidate for environmental remediation methods like photocatalysis, natural chemical nature, and powerful electrochemistry—adsorption, membrane separation, and electrocatalytic sensors for identifying pollution. MXene has strong surface functional groups, an ion exchange property, and an extremely hydrophilic surface. The most recent developments in MXene preparation and characterization for (Ti C Tx) based nano photocatalysts for water remediation and applications are summarized in this review. Additionally, there are difficulties associated with the synthesis and application of MXene for examining and discussing pollution decontamination. This emerging field focuses on utilizing MXene materials to address water pollution issues through photocatalytic processes. Challenges in designing effective MXene-based photocatalysts are explored, including issues related to charge carrier separation, electron transfer dynamics, and optimizing catalytic efficiency. Recent developments and innovative strategies for overcoming these challenges are discussed, highlighting advancements in enhancing photocatalytic performance and improving water remediation capabilities. The synopsis aims to provide a concise overview of the current state of MXene-based nano photocatalysts for water treatment, offering insights into both hurdles and promising breakthroughs in this critical area of environmental research.

1. Introduction

New sustainable water and renewable energy sources are needed to address the increased demand for water and energy due to the quickening rate of global population growth and industry expansion. Two-dimensional (2D) nanomaterials have outstanding performances in several applications due to their distinctive physical and chemical features. Two-dimensional (2D) nanomaterials benefit from distinct ultra-thin layered microstructural qualities and show a variety of unique chemical and physical characteristics, giving them remarkable abilities [1]. With the discovery of graphene, boron nitride nanosheets (BNNSs), transition metal dichalcogenides (TMDs), and black phosphorus (BP), much work has been invested in extending the variety of 2D materials. Specifically, Due to its unique 2D morphology, a plethora of exposed metal sites, versatile chemistries, an abundance of exposed metal sites, and metallic conductivity, a new 2D material of much research interest has been shown called MXene. This makes it suitable for various applications, including energy storage, water purification, sensors, and catalysis [2-5]. The worldview of 2D nanomaterial research has moved to the vast scope and high throughputplanning from the primary materials of nanosheets. In any case, the enormous scope of the creation of MXene using a productive strategy remains a test [6].

Dyes, Heavy metals, pharmaceutically active compounds, endocrine disruptors, and various contaminants have been identified in global water sources, including industrial wastewater, municipal wastewater effluents, and potable water.

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Concentrations of these substances have been detected within a range of 1 mg/L to several mg/L. This presence of pharmaceuticals and endocrine disruptors in water raises concerns about potential impacts on human health and ecosystems. According to numerous previous studies, monitoring and addressing these contaminants in water systems are essential to ensure the safety and sustainability of water resources worldwide. The treatment of various wastewaters containing various contaminants can be accomplished in multiple ways: biodegradation, chlorination/ozonation, Sono degradation, adsorption, and membrane separation. While these methods have some disadvantages,such as high costs, many byproducts, only moderate levels of removal, and photocatalytic degradation, an advanced catalysis method has demonstrated significant benefits, including low costs, complete degradation, environment friendliness, and reusability [7-10]. Photocatalytic CO_2 reduction, nitrogen fixation, and H_2/O_2 evolution have significantly progressed over the past ten years. To split water via photocatalysis and reusability of the MXene membrane, electrons and holes must first be produced by photocatalysts using solar energy, then moved to the catalyst's surface, where they can react with water to produce hydrogen and oxygen Figures 1(a and b) [10-11]. MXene-based nanocomposite membranes also demonstrate versatility and effectiveness across various applications, ranging from water treatment to advanced materials for electrochemical and biomedical purposes. Ongoing research continues to explore and optimize these applications, unlocking the full potential of MXene in membrane technology [12,13]. Figure 1 (a) The g-C_3N_4@MXene/PES (CN-MX) composite membrane removal mechanism for dyes and antibiotics from wastewater. Reprinted with permission from Janjhi et al., [14]. The following is the layout of this review: MXene (Ti C Tx) based nano photocatalysts, its properties, and the most recent developments in green route to synthesize MXene and their potential applications preparation and characterization for (Ti C Tx)-based Nano photocatalysts for water remediation and Sustainable Synthesis Figure 2. Additionally, the difficulties that arise when making MXene to clean up pollutants were looked at and discussed.

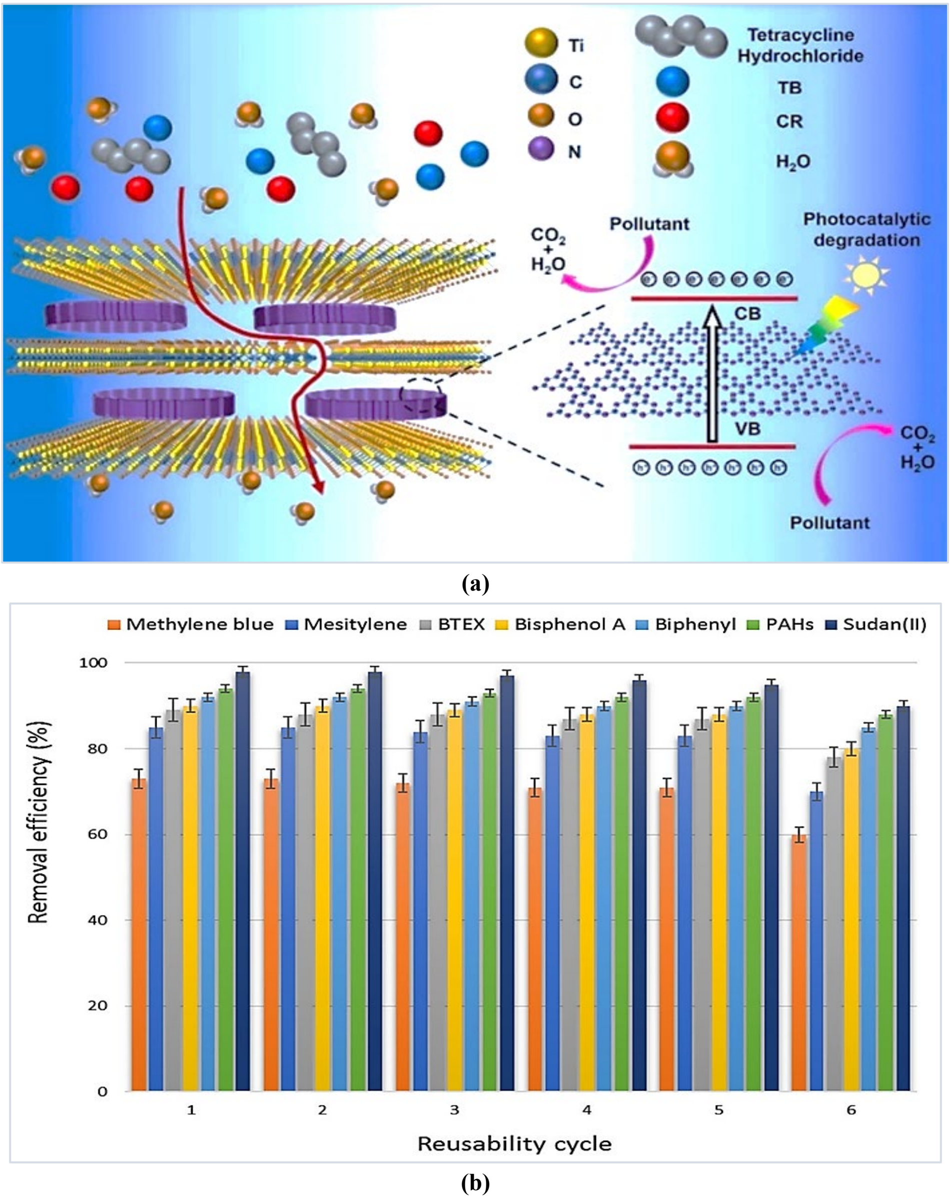


Figure 1: (a) The g-C3N4@MXene/PES (CN-MX) composite membrane removal mechanism for dyes and antibiotics from wastewater. Reprinted with permission [14], (b) Reusability of the MXene membrane [11]

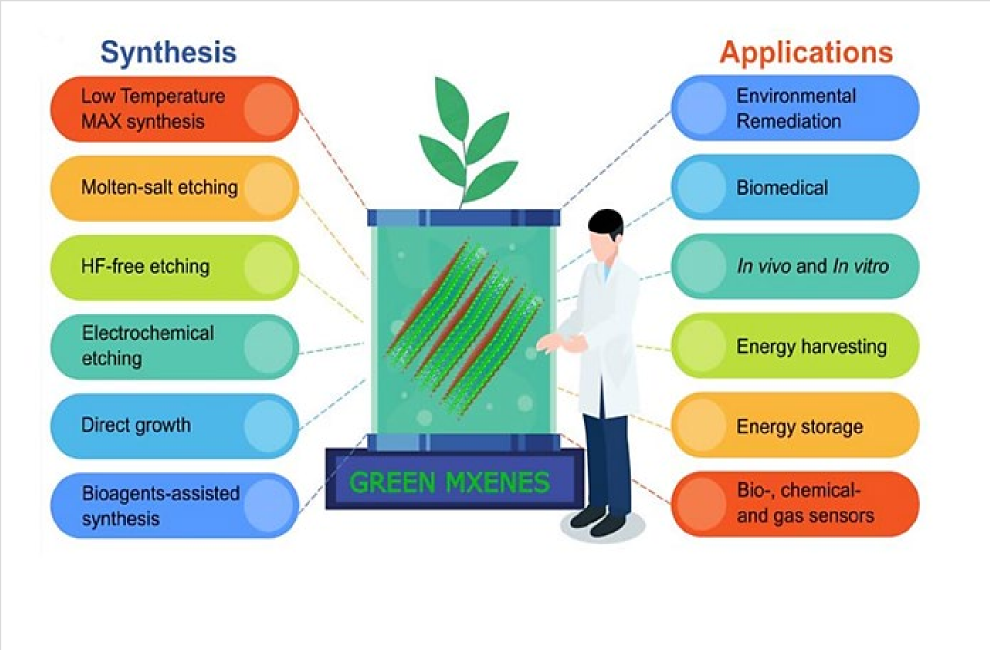


Figure 2: Green route to synthesize MXene and their potential applications [15]

2. MXene (Ti C Tx) based nano photocatalysts

MXene, a brand-new family of two-dimensional materials, was discovered in 2011 by researchers at Drexel University. The transition metal carbides carbonitride and nitrides that make up the MXene family generally have the formula Mn+1Xn, where M stands for transition metals (such as Sc, Mo, Hf, Cr, V, Ti, Zr, Ta, Nb, etc.) n = 1, 2, 3, or 4 deciding the number of nuclear layers in the unit cell) Moreover, X is carbon or potentially nitrogen, and surface terminations like F, O, Gracious, or Cl are marked as Tx [16]. MXene synthesis involves the selective etching aluminum from MAX phases, typically starting with Ti_3AlC_2. The etching process, often using acids like HF or HCl, removes aluminum layers, leaving MXene layers. After washing and delamination, surface functionalization can be applied. Characterization techniques confirm structure and composition. MXene finds applications in energy storage, catalysis, and more due to its unique properties [17]. Topochemical scratching of the forerunner material, usually a Maximum stage, is the most vital phase in the development of MXene. Carbide and nitride layers with a closed-packed hexagonal structure are known as MAX phases. Al, Ga, and Si belong to the periodic table's A-group, denoted by the letter "A" in MAX. MXene quality relies heavily on MAX phases. Specific scratching starts with the evacuation of the A-layer iotas from the Maximum stage and goes on with the delamination and shedding of 2D MXene drops that are free [18]. M2XTx, M3X2Tx, M4X3Tx, and M5X4Tx are the four distinct compositional formulas of MXene that have been synthesized thus far. The most extensively researched MXene is Ti_3C_2Tx, which is an M3X2Tx structure. It was the first MXene to be reported [19], as shown in Figure 3. The synthesis of any MXene can take anywhere from a few hours to a few days, depending on at least one factor: the temperature at which the HF is etched. In the case of Ti_3C_2Tx, for instance, we employed as little as 3% HF-containing etchant. We discovered that the concentration of defects in Ti_3C_2Tx flakes increased with increasing HF content, affecting MXene quality, environmental stability, and properties [20].

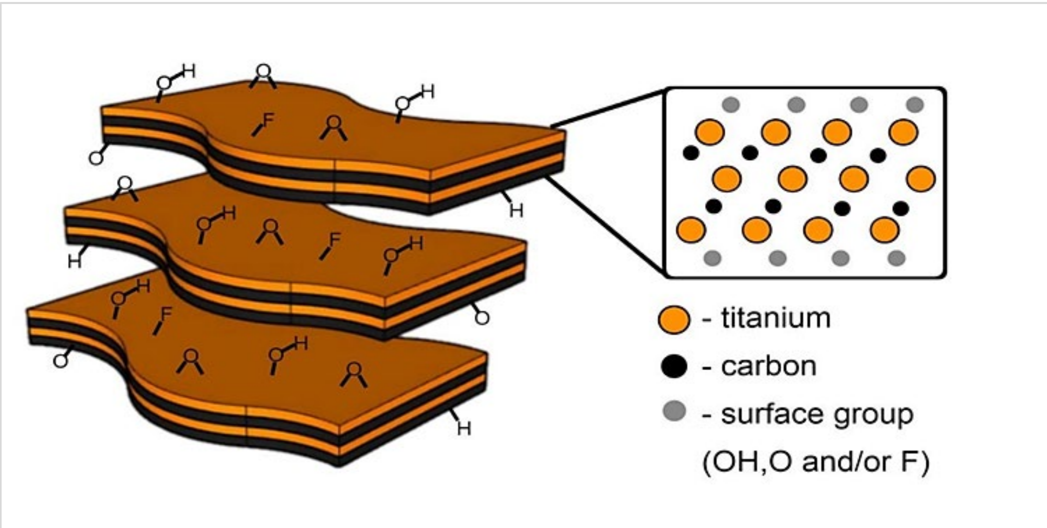


Figure 3: Schematic of Ti_3C_2Tx layered structure with a side view of a nuclear model of a solitary sheet [21]

3. Property type of MXene

Due to their high young modulus, increased electric and thermal conductivities, and significant fluctuating band gaps, MXene is unique. The hydrophilic textures and strong metallic conductivities of MXene should be noted [22].

3.1 Structure

The properties of the MXene structure are crucial for understanding its behavior and applications. After being derived from the MAX phase, MXene terminates with surface groups, such as F, OH, and O. The stability of MXene species is influenced by these surface terminations. The most stable MXene species typically features O or OH terminations. F terminations, initially present, tend to convert to OH groups after washing and storage in water. Moreover, it has been demonstrated that OH groups can transform O terminations through high-temperature processes and metal adsorption techniques. Notably, when MXene with O-ending groups comes into contact with metals like Mg, Ca, Al, or others, it can break further into bare MXene. This interaction underscores the dynamic nature of MXene structure and responsiveness to various environmental conditions and metal interactions. Understanding these structural properties is essential for tailoring MXene for specific applications, ranging from catalysis to energy storage and beyond [23-25]. MXene is a versatile material with applications in wastewater treatment. They can adsorb pollutants, serve as catalysts in advanced oxidation processes, enhance electrochemical treatment, and contribute to filtration and membrane technologies. MXene effectively removes heavy metals, emerging contaminants, and pollutants, making them valuable for water purification. Additionally, their photocatalytic properties and use in sensor platforms further enhance their applicability in wastewater treatment.

3.2 Electronic

The following is a list of the most essential characteristics of MXene families. Modifying functional groups and creating solid solutions can alter the essential MXene properties: electric, electronic, dielectric, magnetic, elastic, thermoelectric, and optical properties of the material [26]. MXene with fewer defects and larger lateral sizes is generally produced using less hydrofluoric acid and etching for shorter periods [27]. Visible absorption and ultraviolet light are additional crucial factors for photovoltaic, optoelectronic, transparent conductive electrode devices and photocatalytic applications. Ti_3C_2Tx films have a UV-Vis retention range of 300–500 nm. Depending on the film's thickness, it may have a larger and stronger absorption band between 700 and 800 nm. The film has a light greenish hue, crucial for photothermal treatment applications [28].

3.3 Electrochemical

MXene exhibits notable electrochemical properties, making it a promising material for diverse applications. Recently, it was found that Ti_3C_2Tx may oxidize in air, CO_2, or pressured water. The oxidation led to the discovery of anatase TiO_2 nanocrystals encased in amorphous carbon sheets (TiO_2-C hybrid structure) [29]. It is known that bare MXene species, like $Ti_{n+1}X_n$, exhibit metallic behavior. However, as the number of Ti-X bonds increases, the metallic properties become less robust. Titanium nitrides exhibit more metallic characteristics in X atoms than titanium carbidesbecause the N atom has one extra electron than the C atom. Ironically, depending on the typesand orientations of surface gathers, terminated MXene sheets are constrained band-hole semiconductors or metals [30]. The top and base Ti layers were predicted to convert into sheets of nanocrystalline rutile during slow oxidation, whereas streak oxidation was predicted to produce somewhat anatase nanoparticles. Two distinct TiO_2 stages were then provided under the two various oxidation systems, as indicated in Figure 4 [31].

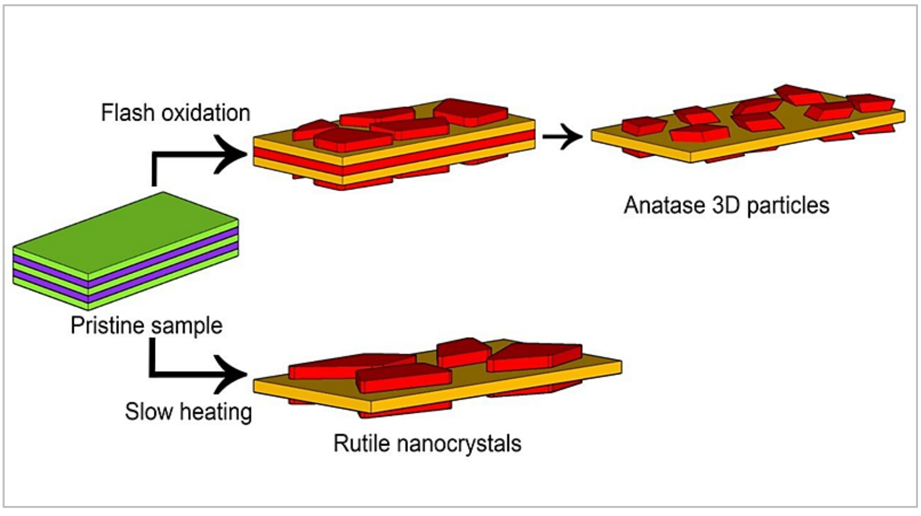


Figure 4: Schematic of the two oxidation instruments [31]

Similarly, it was discovered that Ti_3C_2Tx could react with oxygen to produce TiO_2 in either the rutile or anatase phases. In contrast to the TiO_2-C hybrid structure, the produced anatase nanocrystals were evenly distributed on the 2D Ti_3C_2 layers. The longer reaction time of approximately 40 minutes compared to less than 5 seconds of flash oxidation caused the discrepancy; the carbon that had just formed was unstable. The anatase phase would change into the rutile phase at high temperatures.

Ti_2CTx experienced a similar occurrence almost simultaneously. Anatase TiO_2 formed through heat treatment, transforming into rutile TiO_2 at higher temperatures [32,33]. Furthermore, the electrochemical properties of MXene for several applications are demonstrated in Table 1.

Table 1: Electrochemical properties of MXene for various applications [34]

Application	Electrochemical properties of MXene
- Electro and photocatalysis	Higher electrocatalytic activity and stability. It improved Faradaic efficiency for O_2 reduction and CO_2 reduction reactions. Lower Gibbs free energy is used for the adsorption of reaction intermediates. Improved kinetics and thermodynamics of water dissociation. Increase in catalytic active sites. Improved precious metal anchoring through charge redistribution and coordination.
- Electrochemically responsive	Tunable band gap to match the one required for photon-electron conversion. Improved conductivity and charge transfer lead to higher efficiency of the sensor device. The work function cannot choose between using the MXene electrode as a hole or an electron transport layer. In molecular imprint, improved molecular imprint crystallization leads to higher efficiency.
- Energy-conserving (supercapacitors and batteries)	Increase in electrochemical stability and performance. Ability to tune the interlayer structure and surface area. Increase in electrode conductivity. It improved Liþ/Naþ ion diffusion. A decrease in electrode/electrolyte interfacial impedance. Significantly reduces charge transfer resistance.
- Bio-based electrochemical sensor	Smaller lateral size. Enhanced photoluminescence quantum yield. Increased lifetime. The tunable peak of the photoluminescence emission is achieved through different doping methods. Consequently, quantum dots emitting light of different colors can be combined to produce white light-emitting diodes or lasers. Metallic conductivity with intrinsic functional groups. Spacious matrix for nanoparticle loading. Adequate sites for biomolecule binding led to rapid transduction of signals.
	different colors can be combined to produce white light-emitting diodes or lasers. Metallic conductivity with intrinsic functional groups. Spacious matrix for nanoparticle loading. Adequate sites for biomolecule binding led to rapid transduction of signals.

4. Principle of MXene-based photocatalysis

Photocatalysis is a process that uses light to trigger chemical reactions.MXene, in this context, refers to a class of two-dimensional materials composed of transition metal carbides, nitrides, or carbonitrides. These materials have significant potential in photocatalytic applications [35-37]. The principle of MXene-based photocatalysis involves using MXene as a catalyst to facilitate chemical reactions when exposed to light. The idea is to harness the unique properties of MXene, such as its excellent conductivity, large surface area, and ability to absorb a broad range of light wavelengths. When MXene is exposed to light, it absorbs the energy and generates electron-hole pairs. These electron-hole pairs can then participate in various chemical reactions on the MXene surface or with other environmental substances. This ability to initiate and facilitate chemical reactions under light exposure makes MXene a promising material for water purification, air purification, and energy conversion applications [38-41]. For example, removing antibiotics from water sources is a pressing environmental concern due to its implications for human health and ecosystem sustainability [42]. MXene-based membranes have emerged as a promising solution to address this challenge. With their unique structural and chemical properties, MXene-based membranes exhibit potential in efficiently adsorbing and separating antibiotics from water. This offers a promising avenue for developing effective and sustainable water treatment technologies. This introduction sets the stage for exploring the applications and significance of MXene-based membranes in antibiotic removal [11,12]. In simpler terms, MXene-based photocatalysis is like using a unique material that gets activated when exposed to light, which helps speed up specific chemical processes. This has potential applications in addressing environmental challenges and developing more efficient and sustainable technologies. [43]. By efficiently separating photoexcited charge carriers, two-dimensional MXene materials promise to enhance the performance of photocatalysts as co-catalysts. When a semiconductor is exposed to light, its photoexcited electrons become energized. These energized electrons in the semiconductor's conduction band easily migrate to MXene, attracted by its effective electron-trapping capabilities, facilitating a productive separation of electron-hole pairs [44]. On MXene, the electrons use oxygen to produce O_2, while the h+ ions react with water to form OH radicals. Both the superoxide and hydroxyl radicals then interact with pollutant molecules, leading to the creation of water and carbon dioxide. Simultaneously, the photoexcited electrons traverse the Schottky barrier, rapidly reaching the highly conductive metallic MXene surface. This movement aids in the efficient separation of photogenerated charges within the semiconductor [45,46]. Furthermore, the Schottky barrier acts as a hindrance, preventing photoexcited electrons from MXene from returning to the semiconductor. This barrier ensures that the isolated electrons do not participate in the CO_2 reduction reaction occurring on the MXene surface. The Schottky junction, established by the inherent electric field, significantly amplifies the photocatalytic activity of the MXene/semiconductor photocatalyst [47].

5. MXene-based photocatalyst preparation approaches

Photocatalyst composites involve various techniques, with mechanical mixing, self-assembly, and in-situ decoration/oxidation being the most employed methods. Mechanical Mixing is the most straightforward way to create photocatalyst composites through mechanical mixing. This involves blending different ingredients in a solution or grinding them into powders. It is like mixing various elements, like combining ingredients in a recipe. In this case, MXene-based photocatalysts replace noble metal co-catalysts [48,49]. Self-assembly is a fascinating technique where negatively charged MXene and positively charged photocatalysts are drawn together due to electrostatic attraction. It is like magnets pulling towards each other. This results in the quick combination of these charged materials, forming self-assembled photocatalyst composites Figure 5, which provides a visual representation of different aspects of charge separation in a photocatalyst system with an MXene co-catalyst. Subfigures (a) and (b) depict proposed processes for CO_2 reduction and H_2 generation, respectively. Subfigure (c) illustrates charge transfer at the (001) TiO_2/Ti_3C_2 interface, emphasizing its role. Subfigure (d) presents band alignments and charge fluxes at the (001) TiO_2eTi_3C interface. Overall, the figure offers insights into the complex mechanisms underlying photocatalytic reactions and the synergistic effects of TiO_2 and Ti_3C_2 in these processes. In contrast to in-situ decoration and self-assembly and mechanical mixing, in-situ decoration involves directly adding various components onto the MXene surface. It is as if you are decorating a surface with different elements that allow for creating materials with strong chemical bonds to MXene [50,51]. This can be particularly beneficial in specific designs. To sum it up, these techniques offer different ways to create composite materials with enhanced photocatalytic properties. Whether it is the simplicity of mechanical mixing, the natural combination in self-assembly, or the direct addition in in-situ decoration, each method contributes to developing efficient photocatalyst composites for various applications.

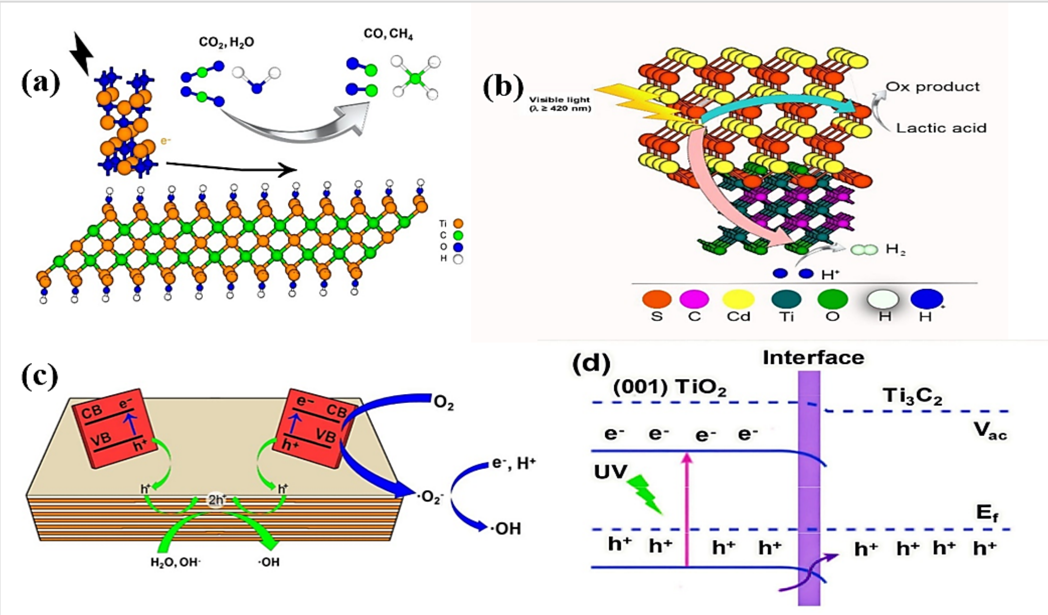


Figure 5: Charge separation diagram for a photocatalyst and an MXene co-catalyst. (a) Ti_3C_2eOH/TiO_2's proposed photocatalytic CO_2 reduction process when exposed to radiation (b) a hypothesis for the CdS/Ti_3C_2 system's photocatalytic H_2 generation process when illuminated by visible light (c) Charge transfer via (001) TiO_2/Ti_3C_2; and d) (001) TiO_2eTi_3C interface band alignments and charge fluxes schematic [49]

6. Applications of MXene in water treatment

The significance of derivatives and MXene in water purification is due to their extraordinary properties. MXene, with many advantages Figure 6, has high electronic conductivity, hydrophilicity, and unique adsorptive, reductive, and antibacterial properties. Water treatment uses Ti_3C_2Tx and its composites most often to eliminate various contaminants [52,53].

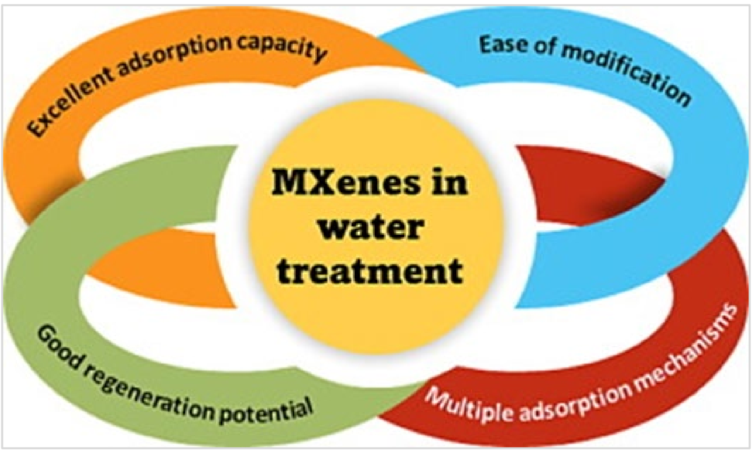


Figure 6: MXene advantages in water treatment [54]

6.1 Heavy metal removal using MXene

The atomic weights of heavy metals typically range from 63.5 to 200.6, and their density is greater than 5 g/cm^3. The wastewater generated by various contemporary chemical industries is the primary source of heavy metals released within the surroundings. Because heavy metals cannot biodegrade like organic pollutants, they tend to build up inside living organisms. The contamination of the amphibian climate because of the release of weighty metals into the biological system has been setting off worldwide nervousness. Mercury, cadmium, Arsenic, nickel-copper, chromium, zinc, and lead are hazardous heavy metals that should be avoided when industrial [55,56]. MXene has shown that it can effectively remove a wide range of heavy metals from water, including cadmium (Cd (II)), copper (Cu (II)), chromium (Cr (VI)), lead (Pb (II)), mercury (Hg (II)), and barium (Ba (II)). Additionally, MXene surface functionalization contributes significantly to the material's capacity for adsorption [57]. Ti_3C_2Tx-based titanium-based MXene is the most used MXene for heavy metal adsorptive uptake. Numerous metal ions have a strong affinity for titanium itself. The MXene layered structure and large surface areas may trap the metal ions. Metal surface functional groups and metal ions exchange ions, resulting in electrostatic interaction. After four adsorption-desorption cycles, the MXene adsorbent showed high reusability with a minor reduction in adsorption capacity. The Freundlich model was used to describe the isotherm data for removing heavy metals from most MXene. MXene is unique in removing pollutants through adsorption and in situ reductions [58,59].

6.2 MXene used as sorption dyes

MXene, with its exceptional properties, has found intriguing applications as a sorbent for dyes in various industries. The term "sorption" encompasses both adsorption and absorption processes, where substances adhere to or are taken up by a material. MXene unique surface characteristics make it well-suited for the efficient sorption of dyes [60,61]. MXene possesses an extensive surface area due to its two-dimensional structure. This feature provides ample space for the adsorption of dye molecules. The large surface area ensures that a significant quantity of dye molecules can be accommodated, enhancing the sorption capacity of MXene. MXene surface can be easily modified and functionalized, allowing for tailored interactions with various dye molecules. This versatility in surface chemistry makes MXene a versatile sorbent for a wide range of dyes, including organic and inorganic varieties. Charged functional groups on the MXene surface facilitate electrostatic interactions with oppositely charged dye molecules [62]. This electrostatic affinity enhances the sorption efficiency, especially for dyes with specific chemical properties. MXene exhibits rapid sorption kinetics, meaning that the adsorption or absorption of dye molecules onto its surface is swift. This quick sorption capability is advantageous for applications where efficient removal of dyes from solution is crucial [63]. MXene stability allows for the regeneration of the sorbent after dye adsorption. This renderability is significant in practical applications, as it enables the reuse of MXene for multiple sorption cycles, contributing to cost-effectiveness and sustainability. The application of MXene as a sorbent for dyes extends to environmental remediation, where removing dyes from wastewater is a critical concern [64]. MXene effectiveness in sorbing dyes makes it a valuable candidate for water treatment processes, helping mitigate environmental pollution. In summary, MXene, when used as a sorbent for dyes, capitalizes on its unique structural and chemical properties. From its high surface area to versatile surface chemistry and electrostatic interactions, MXene is a promising material for efficiently adsorbing and absorbing various dyes. This application holds great potential in addressing environmental challenges and improving water quality [65].

6.3 MXene eliminating radionuclides

Two-dimensional material (MXene) has proven effective in eliminating radionuclides, which are radioactive elements that pose health and environmental risks. MXene large surface area enables efficient contact with radionuclides, while its surface chemistry allows for tailored interactions. Through ion exchange mechanisms, MXene selectively captures radioactive elements. Known for its chemical stability, MXene maintains effectiveness in harsh environments. Moreover, MXene renderability supports repeated use. Applied in environmental remediation and water treatment, MXene removes radionuclides, promoting cleaner and safer ecosystems [66,67].

6.4 Miscellaneous uses for MXene in water remediation

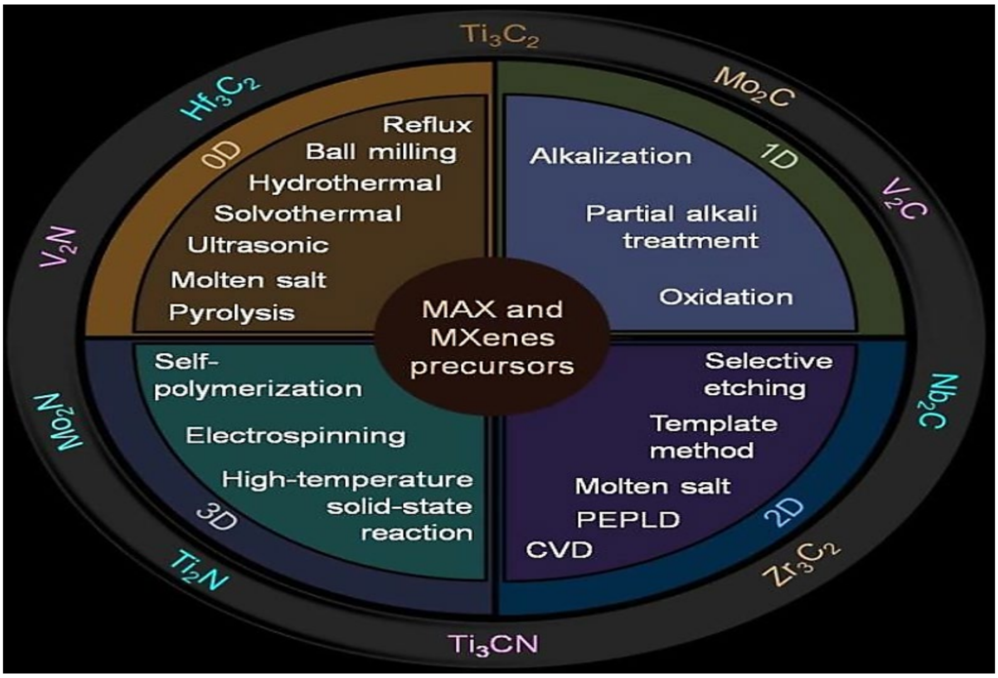
Other environmental uses, including membranes, capacitive deionization, and water purification using an antimicrobial chemical, were also successful when using MXene and its composite. MXene is an exciting option for water purification membranes because of its superior mechanical and electrical qualities, hydrophilicity, and massive surface area. Atoms can be isolated by connecting with the charged MXene layers and by size rejection in the stacked layers. More repressed water particles [68] can be disposed of because of the obliged interlayer dividing of MXene. The membranes based on MXene (Ti_3C_2Tx) had a high water flux and excellent separation potential for various ions based on their charge and hydration radius. In addition to effectively removing dyes, MXene (Ti_3C_2Tx) changed with Ag nanoparticles had strong properties against fouling and bacteria [69]. Since they have a tunable surface, hydrophilicity, and high electrical conductivity, MXene can also be used in capacitive deionization (CDI), making it a potential prominent material for future water desalination [70].

7. Challenges and outlook for the future

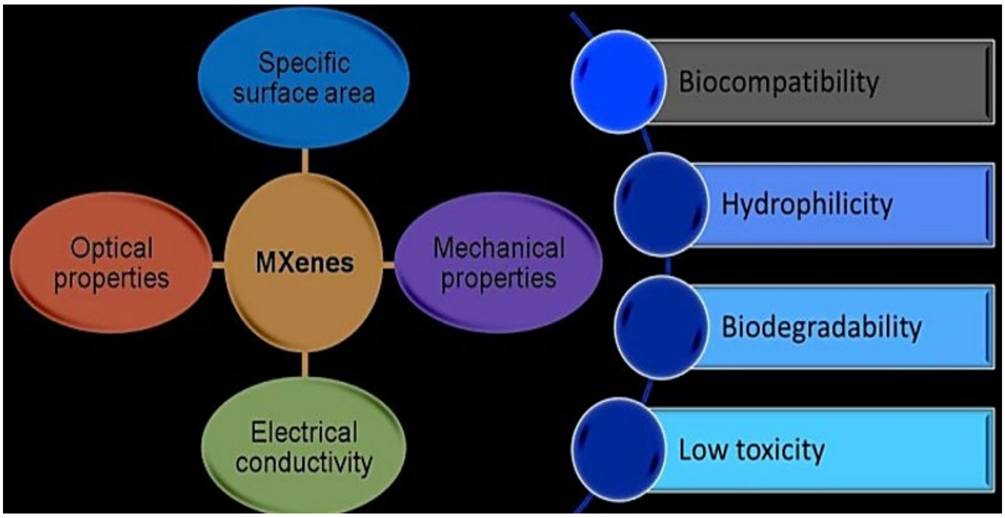
MXene is a superior material for several environmental applications, but many difficulties and unanswered problems remain. A few critical technological challenges are summarized below.

7.1 Synthesis methods

Recent advancements in the fabrication of MXene and its derivatives have seen diverse methods catering to different dimensional forms, including (0D, 1D, 2D, and 3D) structures. Figure 7 provides a dual perspective on MXene materials in biotechnology. Subfigure (a) categorizes recent fabrication methods based on MXene's dimensional forms (0D, 1D, 2D, and 3D), offering a concise reference for researchers seeking specific fabrication approaches tailored to their desired MXene structure; Subfigure (b) details the properties essential for biotechnological applications, including conductivity and biocompatibility. Overall, the figure serves as a comprehensive guide for understanding MXene's potential and the corresponding fabrication methods relevant to biotechnology. This compilation of fabrication methods showcases the versatility of MXene engineering, allowing researchers to tailor its structure in zero, one, two, and three dimensions. These diverse forms open opportunities for MXene applications in various fields, such as electronics and biomedicine. Methods for ordinary MXene production necessitate using HF solution, which can be dangerous. Using green materials for the MXene blend can be an expected leap forward. Few attempts have been made recently to replace the HF using less dangerous chemicals. This prevents MXene properties from being fully utilized in wastewater treatment applications. Another obstacle in the electrical field that requires proper attention is a decrease in MXene conductivity with increasing layers [71].



(a)



(b)

Figure 7: (a) Compilation of recent fabrication methods of MXene and derivatives depends upon their 0D, 1D, 2D, and 3D forms (b) Properties of MXene and MXene-based materials for biotechnology-related applications [71]

7.2 Production on a large scale

The significant expense and poor MXene yield creation are likewise a portion of the principal challenges. MXene has been prepared to yield low in the laboratory until now. Developing environmentally friendly, cost-effective, and efficient preparation methods for industrial-scale production will be essential for real-world uses in environmental domains. In addition, MXene prices are anticipated to decrease following the start of large-scale production [72].

7.3 Thermal and oxidative stability

A significant hurdle MXene materials face in aqueous environments lies in their thermal and oxidative stability. MXene is inherently thermodynamically metastable and exhibits moderate resistance to oxidation in a dynamic aqueous setting. Specifically, Ti_3C_2Tx tends to undergo oxidation, giving rise to TiO_2 due to its limited resistance to oxygen. The metastability of MXene poses a significant challenge for its broader practical applications. In practical scenarios, powdered MXene (specifically Ti_3C_2Tx) may undergo decomposition when subjected to oxygen at temperatures surpassing 200 °C. This decomposition leads to the creation of carbon, TiO_2, and CO, as illustrated in Table 2, demonstrating MXene-based membranes' effectiveness in removing various antibiotics. This decomposition process further emphasizes the vulnerability of MXene to environmental conditions, particularly at elevated temperatures. Addressing MXene metastability is imperative for expanding its practical applications, and one potential approach is modifying the MXene surface, as suggested in previous research [73,74]. This avenue holds promise for enhancing the stability of MXene in various applications.

7.4 Toxicity assessment

Research on the toxicity of MXene materials indicates that, in general, they show good biocompatibility and low cytotoxicity, especially when appropriately functionalized. Limited in vivo studies suggest potential suitability for biomedical applications. Surface functionalization and the specific type of MXene influence toxicity and oxidative stress as a consideration. However, understanding MXene toxicity is still evolving, necessitating further research to comprehensively assess the potential risks and safety implications in Table 3. Researchers and practitioners should stay informed about the latest scientific findings on MXene toxicity [75].

Table 2: Antibiotics removal by MXene-based membranes [48]

MXene-based membranes	Antibiotics	Water permeability (L m-2 h-1 bar-1)	Rejection (%)	Molecular weight (g/mol)	Mechanism
$TI_3C_2T_x$	Erythromycin	278.5 ± 10.5	95 + 1.2	734	Molecular sieving and electrostatic repulsion
	Azithromycin	280.4 ± 15.2	95.1 + 1.6	749	
	Tetracycline	250.4 ± 5.2	91.5 + 0.4	444.4	
	Penicillin				
	Bacitracin	223.1 ± 9.5	89.5 + 0.5	334.4	
	Chloramphenicol	340.5 ± 20.5	99.5 I 0.4	1422	
	Rifampicin	200.5 ± 10.2	89.5 + 0.3	323	
		300.5 ± 10.2	96.2 + 1.8	823	
$g-C_3N_4$@MXene (CN-MX)	Tetracycline hydrochloride (TC)	1790	86	481	Molecular sieving and electrostatic repulsion
$Ti_3C_2T_x$/CNFs (carboxylated cellulose nanofibers)	azithromycin	26.0	~99.0%	749	Molecular sieving and electrostatic repulsion

7.5 Real practical application

The unique properties of MXene, such as high adsorption capacity, catalytic activity in advanced oxidation processes, and excellent electrochemical performance—particularly in combination with photocatalysis—make them novel in wastewater treatment. The two-dimensional structure of MXene enhances filtration, and its easy functionalization allows for the targeted removal of specific pollutants. MXene also exhibits photocatalytic properties, sensitivity for sensing applications, and efficiency in eliminating emerging contaminants, showcasing its versatile approach to water purification. Ongoing research aims to optimize MXene-based materials for innovative and sustainable solutions to water pollution. While MXene has shown immense promise in various environment-related fields at the theoretical and laboratory scale, its real-world practical applications are still in the early stages of exploration. Mixed matrix membranes (MMMs) incorporating MXene have garnered attention due to their potential in various separation and filtration applications. Integrating MXene into MMMs introduces unique properties that enhance the overall performance of the membranes. MXene in Mixed Matrix Membranes enhances their mechanical strength, selectivity, and conductivity. Ongoing research addresses challenges to fully exploit MXene potential in MMMs, opening opportunities for advanced separation technologies with improved efficiency and functionality [76-81]. To truly assess the feasibility and effectiveness of MXene, it is crucial to investigate its performance in simulated industrial settings. For instance, in industrial wastewater purification, where heavy metal ions and biological substances naturally coexist, MXene potential must be rigorously tested. Understanding how MXene operates in such complex and practical scenarios is essential for determining its viability on a larger scale. Moreover, the commercialization of MXene faces significant challenges that need to be addressed before widespread adoption. To make MXene suitable for specific applications, its characteristics must be enhanced. This enhancement process is critical to ensuring MXene possesses the requisite features for practical use in various industries. In essence, transitioning MXene applications from theoretical and laboratory studies to real-world scenarios requires a comprehensive understanding of its performance in complex industrial conditions. Addressing issues and optimizing MXene characteristics will pave the way for its successful integration into practical applications. It will be a significant step toward realizing its potential benefits in industrial and environmental contexts [82,83].

Table 3: Antibiotics removal by MXene-based membranes [76]

MXene-Based Photocatalysts	Pollutants	Advantages/Properties
Carbon nitride coupled with Ti_3C_2 -MXene derived amorphous titanium (Ti)-peroxo heterojunction	Rhodamine B and tetracycline	-High reusability and stability - Superb photocatalytic degradation efficiency over Rhodamine B (~97.22%) and tetracycline (~86.34%) under visible light irradiation (λ > 420 nm) within 60 min
Rod-like Nb_2O_5/Nb_2CTx composites	Rhodamine B and tetracycline	-High photocatalytic degradation of Rhodamine B (~98.5%, 120 min) and tetracycline (~91.2%, 180 min) under visible light irradiation - High photoactivity and cycle stability
TiO_2/Ti_3C_2Tx	Carbamazepine	-High photocatalytic degradation of carbamazepine (~98.67%) under UV light irradiation - •OH and $•O_2$ attacked the carbamazepine molecule during the photocatalytic degradation.
$Ti_3C_2/g\text{-}C_3N_4$	Phenol	- 98% phenol removal efficiency - 32.1% phenol could be degraded under dark conditions owing to the capability of MXene to store additional photo-generated electrons under light irradiation and release them when exposed to electron acceptors in dark conditions
$CuFe_2O_4/Ti_3C_2$	Sulfamethazine	-The synergistic degradation effects under visible light - The breaking of S–N bonds could be detected; the oxidation of aniline and deamination were dominated by attacking •OH
Bismuth/bismuth oxychloride (Bi/BiOCl) microspheres/Ti_3C_2	Ciprofloxacin	-Excellent reusability in the 5 cycles of ciprofloxacin degradation - High photocatalytic performance

8. Conclusion and Future Prospects

MXene-based nano photocatalysts show tremendous promise in water remediation. The diverse range of MXene nanoarchitectures presents an exciting avenue for further exploration. Notably, the comparison between lightweight MXene (Ti_2CTx) and its heavier counterpart (Ti_3C_2Tx) has been extensively discussed, emphasizing the need for a deeper understanding of the various synthesis strategies employed. While significant strides have been made in researching MXene functionalization, there remains a crucial need for investigations that focus on the adsorptive nature of MXene independent of functional groups. This approach will contribute to a more comprehensive understanding of MXene intrinsic adsorption capabilities and broaden their applicability in water treatment. The two primary synthesis methods, involving the exfoliation of crystals into single-layered MXene sheets and the growth of MXene from atoms or molecules, provide unique opportunities for tailoring MXene properties. Future research should delve into optimizing these methods to enhance the efficiency of MXene-based adsorbents for diverse water pollutants.

In the realm of environmental applications, various mechanisms such as internal circle complexation, ion exchange, chemisorption/physisorption, electrostatic attraction, and hydrogen bonding have been identified as critical processes underlying the effective removal of radionuclides, metals, and dyes using MXene. Understanding and fine-tuning these mechanisms will pave the way for developing highly efficient and selective MXene-based adsorbents. Transitioning to MXene-based membranes, it is evident that despite the substantial progress, challenges persist in achieving effective membrane development. Overcoming these challenges will require concerted efforts in refining synthesis techniques, optimizing membrane structures, and addressing scalability and long-term stability issues. In the future, continued interdisciplinary research is essential to unlock the full potential of MXene-based materials in water remediation. This involves delving into novel synthesis routes, understanding fundamental adsorption mechanisms, and overcoming obstacles in membrane development. By addressing these aspects, MXene-based adsorbents and membranes can emerge as pivotal players in sustainable water treatment technologies, contributing to the global pursuit of clean and safe water resources.

Author contributions

Conceptualization, K. Abbas and A. Al-Ghaban; methodology. H. Abbas; software, H. Abbas; validation, K. Abbas, H. Abbas and A. Al-Ghaban; formal analysis, H. Abbas; investigation, K. Abbas; resources, H. Abbas; data curation H. Abbas; writing—original draft preparation, H. Abbas ; writing—review and editing, H. Abbas ; visualization, K. Abbas; supervision, K. Abbas; project administration K. Abbas; All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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