Two dimensional MXenes as emerging paradigm for adsorptive removal of toxic metallic pollutants from wastewater

# Two Dimensional MXenes as Emerging Paradigm for Adsorptive Removal of Toxic Metallic Pollutants from wastewater

Tahir Rasheed[a]*, Fahmeeda Kausar[b], Komal Rizwan[c] Muhammad Adeel[d], Farooq Sher[e], Norah Alwadai[f], Fwzah H.Alshammari[g]

[a]Interdisciplinary Research Center for Advanced Materials, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia.

[b]School of Chemistry and Chemical Engineering, Shanghai Jiao Tong University, Shanghai 200240.

[c]Department of Chemistry University of Sahiwal, Sahiwal, 57000, Pakistan.

[d]Faculty of Applied Engineering, iPRACS, University of Antwerp, 2020 Antwerp, Belgium

[e]Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, United Kingdom.

[f]Department of Physics, College of Sciences, Princess Nourah bint Abdulrahman University (PNU), Riyadh 11671, Saudi Arabia.

[g]Department of Physics, University Colleges at Nairiyah, University of Hafr Al Batin (UHB), Nairiyah 31981, Saudi Arabia

*Corresponding author emails: masil@sjtu.edu.cn; tahir.rasheed@hotmail.com (T. Rasheed).

**Abstract**

Effective methods for removing harmful metals from wastewater have had a huge impact on reducing freshwater scarcity. Because of its excellent removal effectiveness, simplicity and low cost at ambient conditions, adsorption is one of the most promising purifying approaches. MXene-based nanoarchitectures have proven to be effective adsorbents in a variety of harmful metal removal applications. This owes from the distinctive features such as, hydrophilicity, high surface

area, electron-richness, great adsorption capacity, and activated metallic hydroxide sites of MXenes. Given the rapid advancement in the design and synthesis of MXene nanoarchitectures for water treatment, prompt updates on this research area are needed that focus on removal of toxic metal, such as production routes and characterization techniques for the advantages, merits and limitations of MXenes for toxic metal adsorption. This is in addition to the fundamentals and the adsorption mechanism tailored by the shape and composition of MXene based on some representative paradigms. Finally, the limits of MXenes are highlighted, as well as their potential future research directions for wastewater treatment. This manuscript may initiate researchers to improve unique MXene-based nanostructures with distinct compositions, shapes, and physiochemical merits for effective removal of toxic metals from wastewater.

**Keywords:** 2D-MXenes; MXene nanocomposite; wastewater; Adsorption; Toxic metal Pollutants

## 1. Introduction

As fast industrialization continues, various toxins have been released into water without being properly cleaned, causing serious environmental contamination and danger to human health (Jasper et al., 2017). Generally, Organic and inorganic pollutants are the two types of contaminants that can be found in the environment. Typical dye compounds such as methylene blue, which are released by manufacturers making paper, paint, textiles, and other products, are among the organic pollutants (Karaçetin et al., 2014). While heavy metal ions (HMIs) and radionuclide are among the inorganic pollutants in wastewater (Ahmad and Mirza, 2018; Mirza and Ahmad, 2018; Zhang et al., 2018). Because of their carcinogenicity and toxicity, they have adverse impact on natural environment and living organisms in general. Some of the maximum allowable contaminant level of heavy metals are as follows, Arsenic: .05 mg/l, Cadmium: .005 mg/l Lead: .015 mg/l, Mercury: .002 mg/l, Chromium: .1, Selenium: .05 mg/l, Antimony: .006 mg/l. Because some of them can

bioaccumulate, the harm they cause to living organisms may be greater than that caused by pollutants that cannot bioaccumulate (Berrios et al., 2012; Karaçetin et al., 2014). As a result, one of the most important predictors of long-term industrial prosperity has been the deployment of effective treatment procedures for the elimination of harmful toxins.

Adsorption is one of the most extensively employed technique for the purpose due to its appealing properties such as simplicity, cost-effectiveness, and applicability (Ahmad and Mirza, 2018; Burakov et al., 2018; Mirza and Ahmad, 2018; Wu et al., 2019; Mittal et al., 2021). Furthermore, using adsorbent to remove toxicants minimizes the production of secondary pollutants because the adsorbents absorb rather than reacting with the contaminants (Wu et al., 2019). A number of documented reports are present in the literature, which discuss the utility of powdered or granular activated carbon, chitosan, and kaolin etc. are the few among many to be used as adsorbents for the purpose (Oguz and Keskinler, 2005; Wang et al., 2010; Zhu et al., 2010). The greater surface area and high porosity of these materials makes them an ideal candidate for the environmental remediation. Recently, an emerging class of nanomaterials such as two-dimensional (2D) have extensively been exploited for the efficient removal of a variety of environmental contaminants. The distinctive features of these 2D nanomaterials warrant their applicability in adsorptive removal (Fu et al., 2018; Wu et al., 2019). The use of nanomaterial-based adsorbents for the treatment of organic and inorganic contaminants in water has increased due to the unique features of 2D nanomaterials, i.e. carbon-based nanomaterials (Atkovska et al., 2018). Nanomaterial-based adsorbents frequently have thin structures, large specific surface areas, and plentiful functional sites, as compared to the huge and bulkier construction of traditional adsorbents (Zhang et al., 2018). Because adsorbents must have a high level of contact with adsorbates and a sufficient surface area to function well, hence the nanomaterials are thought to have the ability to address

both inorganic and organic adsorbates(Yang et al., 2019). MXene, a new class of 2D nanomaterials derived from a family of transition metal nitride or carbide compounds, has recently piqued interest in a variety of fields.

Owing to their excellent properties such as greater surface area, eco-friendly, greater chemical stability, hydrophilicity, and electrical/thermal conductivity, MXenes are ideal materials for a variety of applications, such as hydrogen storage (Hu et al., 2013), lithium-ion battery (Naguib et al., 2012), supercapacitor (Zhu et al., 2016), semiconductor (Gao et al., 2016), and environmental applications (Ciou et al., 2019). Particularly, the probable environmental applications comprise of membrane filtration, photocatalysis and adsorption to eradicate contaminants, via MXenes and MXene-based composite materials as adsorbents for the elimination of inorganic and organic pollutants from water have extensively been studied (Rasool et al., 2017).

Herein, the main purpose of the study is to comprehend the overall knowledge of MXenes and their composites as potential adsorbent for the removal of inorganic impurities such as heavy metal ions and radionuclides from water. In order to achieve the goal, this study will focus on the key aspects of manipulating the composition and shape of MXenes and MXene based nanocomposites for the removal of toxic metal from wastewater, such as manufacturing strategies and characterization methodologies, as well as their formation mechanisms. The limitations and advantages of these materials as adsorbents of toxic heavy metals and radionuclides are reviewed, along with their adsorption mechanism, supported by several descriptive paradigms. Then, perspectives and outlooks for future research in the field of removing these analytes (heavy metal ions and radionuclides) are suggested.

## 2. Characterization of MXenes and Their Preparation

MXenes, a potentially new class of two dimensional (2D) materials, have been the subject of a number of recent book chapters and review papers that have discussed their distinctive features, potential applications, and syntheses (Ng et al., 2017; Zhang et al., 2018; Habib et al., 2019; Melchior et al., 2019). As a result, the focus of this review is solely on the adsorption behavior and characterization of certain MXene structures in wastewater treatment, with an emphasis on particle entrapment methods and the significance of unique surface functionalization in operational efficiency. The term "MXenes" represents a class of nanoparticles, sharing the general formula based representation as $M_{n+1}X_nT_x$ (n = 1–3). In this formula M stands for transition metals such as, Mo, Nb, Sc, Hf, Cr, Ti, Ta, Zr, V, etc. while X is a carbon or nitrogen atom and $T_x$ is the variable surface termination which is highly dependent on the manufacturing method and requirement of properties of the formed MXene. These terminals may include fluorine, oxygen or hydroxyl moieties but not limited to them. The development in the field of MXenes as 2D materials using different methods and raw materials is becoming increasingly popular which is also emerging a new three dimensional (3D) constructs/architectures (Ng et al., 2017; Xiu et al., 2018). The layered architecture of M (n + 1) and X (n) layers respectively, which are termed 3D pores inside their nanoscale configuration, is what brands MXenes so intriguing (Anasori and Gogotsi, 2019). While the majority of MXenes are made up of just one transition metal, some varieties exist in which more than one metal is involved, either in a layered fashion, random distribution or in well-ordered pattern. Generally, the selective etching by A group elements using their MAX phase is applied for the fabrication of MXenes. The layered nitrides and carbides (X-elements) represents the MAX phase in MXenes structure which are sandwich between A layers of group III A/IVA such as Si or Al (not limited to them may also include Pb, P, As, S, Ga, Sn, Ge, In, Cd, and Tl) and M layers of transition metals (Anasori and Gogotsi, 2019). Among the most commonly

commercially available MAX phase employed is $Ti_3AlC_2$. As a result, the majority of MXenes research focuses on those with the formula Ti3C2Tx, where T stands for surface terminations like $^{-}OH$, $F^{-}$, or $^{-}O$. The selective chemical etching methodology is being employed for the fabrication of $Ti_3C_2T_x$. The hydrofluoric acid (HF) is used as an etching agent, accompanied by the use of dimethyl sulfoxide as delaminating agent under sonication. Moreover, to create fluoride free surface termination the dry etching technique is widely exploited in comparison to wet etching. This can increase the suitability of activating the MXenes surface and its applicability in a broader context. The stacking of MXene layers and effects of various delamination and etching procedures on generated MXene formulae are portrayed in Figure 1 (Alhabeb et al., 2017). Herein, the influence of various preparatory methods of MXene and their structure, morphologies, and surface terminations are examined in relation to the hazardous metal. Before going into depth about MXenes' ability to remove harmful metal particles, it's important to note that one of the most significant roadblocks to MXenes' commercialization is its thermodynamically metastable condition. The remarkable high surface energy of MXenes, especially makes them highly susceptible to degradation. MXene solutions, in particular, oxidize over time, creating $TiO_2$ crystals at the boundaries of MXene flakes and eventually transforming the entire structure into carbon sheets and $TiO_2$. The difference between the oxidized and pristine MXene can be clearly marked by discerning the difference in color, as the oxidized solution colored as cloudy white or gray while the pristine MXenes are greenish black in color to the naked eye.

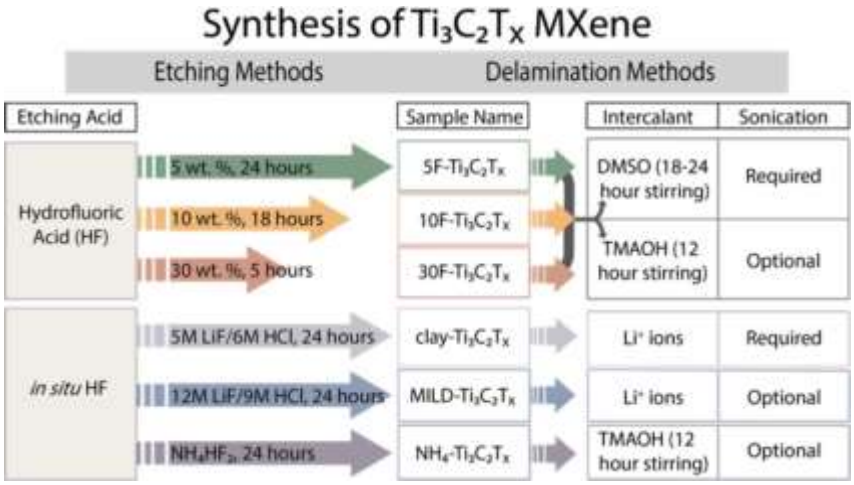



**Figure 1.** Preparation of $Ti_3C_2T_x$ using different synthesis routes (direct HF and in situ HF). Reproduced with permission from (Alhabeb et al., 2017). Copyright 2017 ACS.

Generally, the MXenes powder are robust and stable in an oxygen rich atmosphere below 200 ˚C (Zhang et al., 2017). For the remediation of toxicant such as metals, $TiO_2$ is an effective adsorbent for a variety of analytes including chromium (Almeida et al., 2019), mercury (Ghasemi et al., 2012) and copper (Cheng et al., 2019). Consequently, a number of MXene based materials are purposely venerable in hydrothermal environments to attain $TiO_2$ as surface elements. Multiple stabilizing strategies for MXene flakes have been investigated, including the use of carbon nano-plates. This results in the creation of new MXene hybrids reinforced with $MoS_2$ and carbon accompanied by the high energy mechanical milling in DMSO demonstrating that the addition of fluorine to their surfaces can achieve high stability (Wang et al., 2016; Wu et al., 2017). Prospectively, MXene based compounds with greater shelf lives and higher stability are predicted to be used in management of wastewater applications by taking fact that the MXene flakes are exposed to aquatic environment. The fast degradability and fragility of MXenes should be accountable when designing the systems for the remediation of targeted toxic metal. The profligate conversion of MXenes into environment friendlier components is advantageous, which may

facilitate the operational simplicity in handling the resultant slurry to be used in wastewater management. Further investigations are needed to be carried out in defining their ranges of operation and final efficiency, more research into the applications of MXenes in water treatment, as well as their breakdown after binding with harmful metals or other harmful wastes, is required.

## 3. Methods and factors effecting for the Removal of Toxic Metal from Wastewater

Over the last few decades, various wastewater management systems have been developed (Burkhard et al., 2000). Among them, reverse osmosis, precipitation, adsorption ion exchange, membrane filtering, and electro-kinetic techniques are all traditional methodologies used for the removal of harmful metal (Vardhan et al., 2019). Even though some of these approaches, such as adsorption and ion exchange, are often employed concurrently, majority of them are used in tandem to isolate the harmful metal and other particles using isolation chambers or reverse osmosis. As a result, the poisonous metal solutes are subsequently converted to solid compounds using adsorption, precipitation, electro-kinetics, a chelating agent or coagulation, and subsequently filtered using different membranes or other collecting methods. Further, the preprocessing stages may involve the addition of some chemical agents or lime to achieve an ideal pH level, as well as temperature and fluid flow modifications, depending on the type of technique utilized. Moreover, post-operational processes can show a discrepancy but predominantly include dewatering, solid precipitates separation, transporting the solid waste to a landfill, as well as further treatment of the residual fluid till a suitable set of provisions is attained that sanctions it to be reverted to nature (Bhojwani et al., 2019; Ijanu et al., 2020). The formation of secondary pollutants in case of chemical precipitation, fouling and susceptibility by organic matter in the case of membranes, a limited ion removal margin, and a high energy cost in the case of electro-kinetic remediation are all obvious drawbacks in traditional wastewater treatment. Adsorption has showed promise among

all existing technologies due to its speedy operation and simplicity, specifically with the development of adsorbents that eliminate the requirement for secondary contaminant and processing. Eternally more and more inorganic and organic materials are being documented as potential adsorption mediators for the removal of toxic metal, such as activated carbon, rice husk, various bacterial species, palm fiber, chitosan, eggshells, clay, clinoptilolite, plants, and different types of nanomaterials (Ngah et al., 2011; Lim et al., 2018; Sherlala et al., 2018). Among them nanoparticles, whether inorganic or organic, have the most outstanding adsorption properties of all existing adsorbents, and some of them are already being used in the wastewater management business. In comparison to other adsorbents or chelating agents, the nanomaterials offer greater efficiency in handling the toxic metal pollutants. This high efficiency in remediating the metal based pollutants owes from the fact that the nanoparticles have high surface area and unique surface properties (Lim et al., 2018). Their surface characterization via different activation processes may enable harmful metal selectivity, allowing for future recycling of these particles rather than their disposal as toxic waste. The metal-organic frameworks (MOFs), Zeolites, bacterial exopolysaccharide, ceramics, algae, and carbons are examples of such type of nanomaterials. Activated carbon is the most extensively utilized nanomaterial in wastewater management, despite being a somewhat expensive choice (Skouteris et al., 2015; Dias and Petit, 2016; Gupta and Diwan, 2017; Ahmadijokani et al., 2021). Future 2D nanostructures are rapidly improving in this ever-growing category because they have higher adsorption abilities due to their large functionalized surfaces with unique features that allow them to be integrated into a variety of wastewater treatment processes, either as adsorbents, catalytic and/or antibacterial agents, or functional membranes. The technique is still developing, and facing a number of issues in immediate commercialization of these materials. These drawbacks involve their short life span and

incompetent integration in the existing architecture of wastewater management systems (Rasool et al., 2019).

### 3.1. Effect of pH

The pH of the medium mainly effects the charge density and degree of ionization of the adsorbent and greatly affect the removal of metals. As at higher pH, hydroxide of metals are formed in the form of salts and become precipitate out from the system. This dependency mainly depends on element of adsorbent and chemistry of solution. The zeta potential measurements of MXene shows high charge density at pH lower than 2.41. In this way, the surface of the adsorbent can be negatively charged, positively charged or become neutral depending pH of the system.

## 4. MXene and MXene based composites for Toxic Metal Removal

### 4.1. Removal of Lead by MXene and MXene based composites

Lead is toxic metal that is produced from agricultural and industrial processes. High concentration of lead in aqueous matrices destroys the health of living beings. Peng and his colleagues used 2-D alkylated MXene ($Ti_3C_2(OH/ONa)xF_{2-x}$) to adsorb Pb (II) from aqueous matrices in 5% sodium hydroxide solution for intercalation of sodium ions (Peng et al., 2014). Successful intercalation of sodium ions took place and they lead to expand the space among layers which enhanced the rate of diffusion of area which may react with Pb(II) ions. Significant adsorption of Pb (II) (140 mg/g) was observed and equilibrium was attained in 120s. The mechanism involved in this study was ion exchange. Presence of various elements like Ti, F, Na, O, and Pb was confirmed through elemental analysis and it was proposed that intercalated $H^+$ and $Na^+$ ions attached to Ti-O (negatively charged species) could exchange with Pb(II) (Giammar et al., 2007). Lead sorption on MXene flakes was found pH dependent and maximum adsorption was obtained in pH range of 5-7 ensuring ion

219 exchange as mechanism of action. At low pH values, MXenes showed less affinity towards Pb(II)
220 ions which assist in regeneration of used MXene in acidic media. MXene material retained
221 selectivity towards Pb (II) ions with efficacy of 95.2%. Jun and his colleagues used the MXene
222 ($Ti_3C_2T_x$) for removal of Pb(II) ions. MXene showed efficient adsorption and it was explained
223 through pseudo-second-order kinetic and the Freundlich isotherm models and equilibrium was
224 obtained in 30 min. MXene exhibited excellent reusability until four cycles (Jun et al., 2020a). Gu
225 and his colleagues synthesized two different MXenes named e-TACFs and e-TACSs through
226 hydrothermal method. e-TACFs and e-TACSs showed maximum adsorption of lead ions 284.9
227 and 218.3 mg/g respectively. Ion exchange and complexation were found as mechanistic way of
228 interaction of lead ions with MXenes which enhanced the adsorption potential. DFT studies
229 supported the results (Gu et al., 2018b). The $Ti_3C_2T_x$ powder contains great ion exchange potential
230 but they show poor adsorption of heavy metals. Du and his colleagues overcome this drawback by
231 regulating $Ti_3C_2T_x$ powder with silane coupling agent (KH570) and they were found efficient for
232 removal of lead ions. The modified powder possessed great surface area, thermal stability and
233 good ion exchange potential. The $Ti_3C_2T_x$ -KH570 powders showed adsorption potential of 147.29
234 mg/g of Pb(II) ions while adsorption potential of pristine $Ti_3C_2T_x$ powder was only 48.28 mg/g.
235 hydroxyl groups of internal MXene were found responsible for adsorption of lead ions. The lead
236 ions adsorption was dependent on availability of hydroxyl and carbonyl moieties of MXenes and
237 KH570 respectively. Thus modified MXenes may be promising for removal of lead ions (Du et
238 al., 2019). Similarly, in a latest study, $Ti_2CT_X$ MXene sheets were functionalized with three
239 different biosurfactants as chitosan, lignosulfonate and enzymatic hydrolysis lignin. The
240 enzymatic hydrolysis lignin functionalized MXene showed high adsorption (232.9 mg/g) of Pb(II)
241 ions and this may be attributed to prevention of $Ti_2CT_X$ nanosheets from restacking and

incorporation of active functional moieties in MXene nanosheets due to enzymatic hydrolysis lignin biosurfactant (Figure 2) (Wang et al., 2020b). MXene has limited adsorption potential for metal ions and this may be because of limited adsorptive active sites. Dong and his colleagues synthesized MXene/alginate nanocomposite for adsorption of lead from aqueous solution (Figure 3). This synthesized composite enhanced the adsorption potential and chelation capacity of Pb (II) ions. Maximum adsorption of Pb (II) was found to be 382.7 mg/g and equilibrium was reached within 15 mins. MXene/alginate composite can be regenerated with facile acid treatment without loss in activity. So this study showed that composites of MXenes may open new dimensions for high adsorptive removal of heavy metals with high efficacy at low temperature (Dong et al., 2019b) (Table 1).


**Figure 2:** Biosurfactant functionalized $Ti_2CT_X$ MXene for adsorption of Pb(II) ions (Wang et al., 2020b)

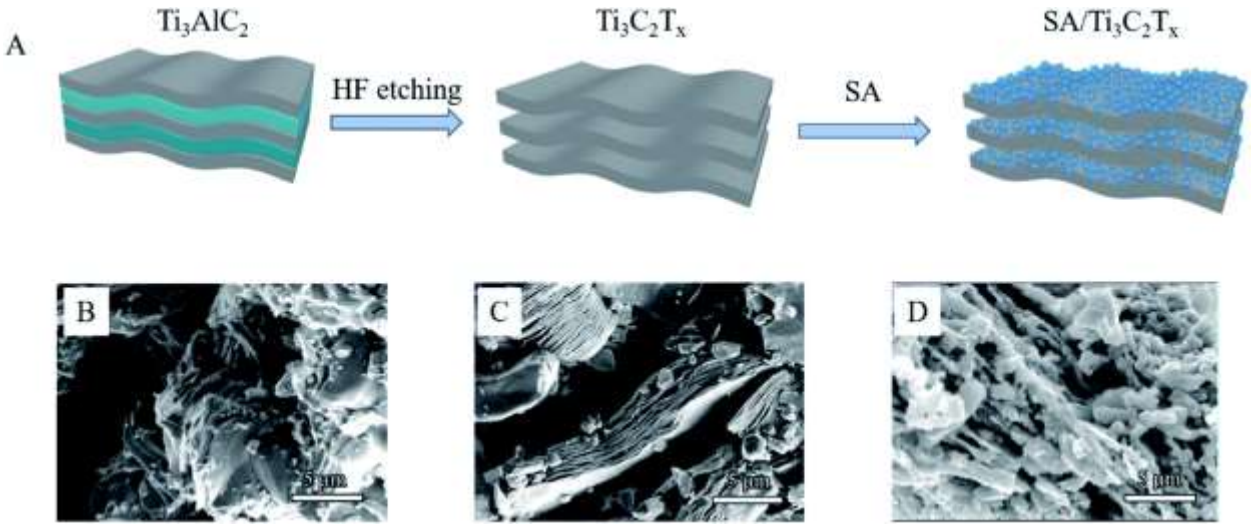



**Figure 3:** (A) Schematic of the preparation of the MXene/alginate composites; (B) surface morphology of $Ti_3AlC_2$; (C) surface morphology of $Ti_3C_2T_x$; (D) surface morphology of the MXene/alginate composites (Dong et al., 2019b). This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

### 4.2. Reduction and Removal of Chromium Ions by MXene and MXene based composites

Chromium is toxic metal that is produced from different industries. Chromium may exist in trivalent or hexavalent forms. Hexavalent chromium is carcinogenic. MXenes are known for adsorption of high valent metal ions. Ying and his colleagues employed MXene nanosheets ($Ti_3C_2T_x$) for adsorption of Cr(VI) (Ying et al., 2015). MXene nanosheets efficiently adsorbed the chromium metal ions with adsorption potential of 250 mg/g. Below pH 2, Cr(VI) were adsorbed on positively charged nanosheets (due to presence of hydroxyl moieties) then hexavelnt chromium would reduce to trivalent chromium via electron transfer (Figure 4). Increase in pH would weakens the electrostatic force of interactions, untill pH reaches 13 and it stops completely. On contact with MXene sheets the chromium metal is reduce with assistance of $H^+$ ions and precipitates (pH 4.8) and full precipitates are obtained at pH 5.6 where trivalent chromium may bind to MXene surface in covalent manner via titanoium oxide sites with 98% removal potential. Sheets may be degraded after use Urchin likr rutile MXene based TiO2–C/TiC nanocomposites were fabricated and they

showed high adsorption of Cr (VI) with adsorption potential of 225 mg/g (Zou et al., 2016). MXene flakes were used by group of scientists to adsorb chromium with adsorptive potential of 80 mg/g at room temperature (Tang et al., 2018).

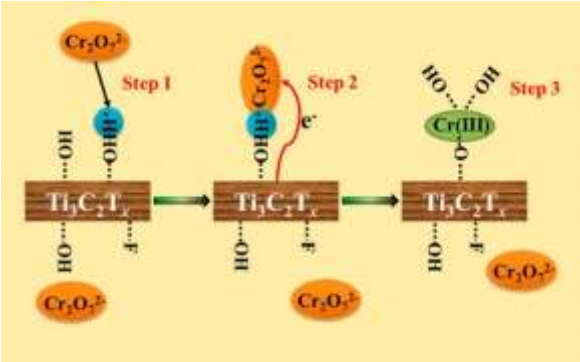
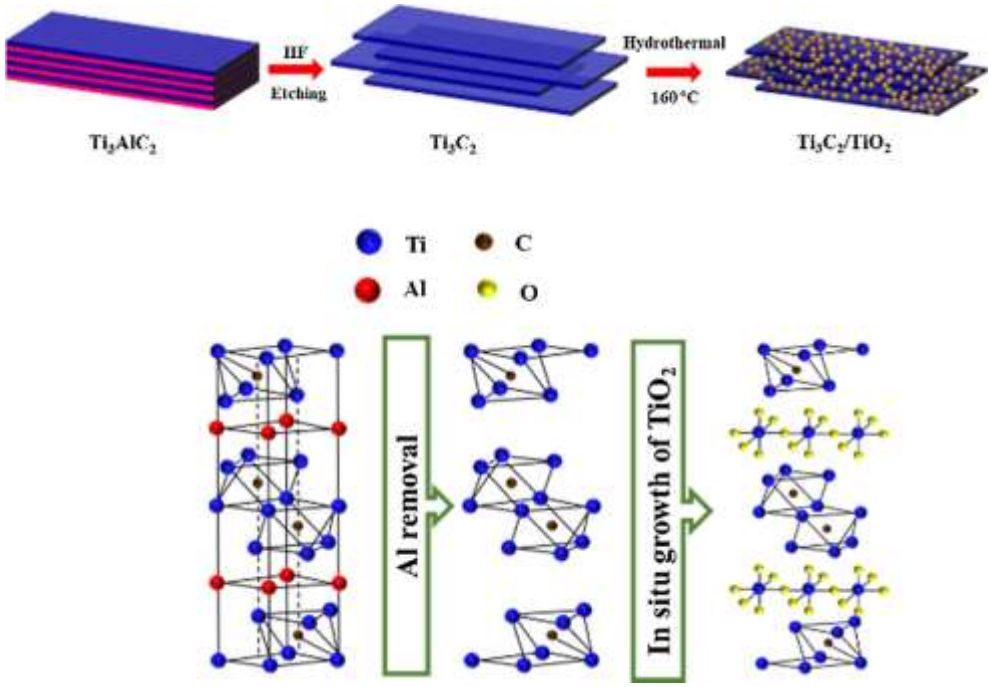



**Figure 4**: Illustration of the removal mechanism of (a) Cr(VI) by the Ti3C2Tx nanosheets. Reprinted with permission from Ref. (Ying et al., 2015)

The $Ti_3C_2/TiO_2$ composite attained effective removal of Cr(VI) from $K_2Cr_2O_7$ solution. The mechanism involved is reduction of hexavalent chromium to trivalent chromium and then adsorption of produced Cr (III) ions (Wang et al., 2020a). After synthesis of MXene flakes the hydrogen fluoride was employed as etchant and obtained Ti3C2 was heated hydrothermally to grow $Ti_3C_2/TiO_2$ particles (Figure 5). The 24 h hydrothermal treatment gives optimum Cr (VI) adsorption with reduction efficacy of 99.35%. Karthikeyan and his collegues used 2D MXenes for removal of Cr(VI). The removal rate of Cr (VI) was quick and reaction followed the second order kinetics. Maximum adsorption capacity of Cr (VI) was found to be 104 mg/g. The MXene sheets were regenerated by using 0.1 M sodium hydroxide solution. Adsorption phenomena involved were electrostatic, complexation, surface interaction and ion exchange for uptake of Cr (VI) ions (Karthikeyan et al., 2021) Recently amino functionalized MXenes ($NH_2$-$Ti_3C_2T_x$) were synthesized. Amino moieties and $Ti_3C_2T_x$ sheets show synergistic effects in adsorption and reduction of Cr (VI). The $NH_2$-$Ti_3C_2T_x$ showed maximum adsorption potential of 107.4 mg/g for

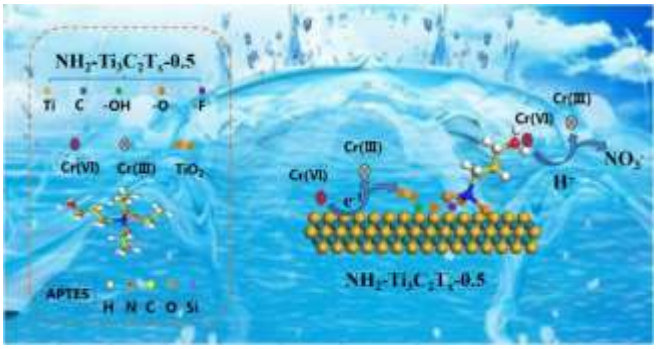
290 Cr(VI) (Kong et al., 2021). Ti (II) and $NH_3^+$ oxidized in Ti(IV) species and $NO_3^-$ during the
291 removal of Cr(VI). Amino functionalized MXene sheets showed great reusability and selectivity
292 (Figure 6). Khan and his colleagues synthesized MXene and δ-$MnO_2$/MXene hybrid through
293 hydrothermal method for adsorption of Cr (VI). The pseudopseudo-second-order model was
294 followed. Adsorption of Cr (VI) was pH dependent. MXene and δ-$MnO_2$/MXene hybrid showed
295 maximum efficiently adsorbed the Cr (VI) with adsorption potential of 273.1 mg/g and
296 353.87 mg/g respectively. The hybride of MXene with transition metal oxides showed highest
297 adsorption potential and this may provide opportunity to remove heavy metals with efficiency due
298 to electrostatic interactions (Khan et al., 2021). Composite of MXene with PEI modified sodium
299 alginate aerogel was synthesized for removal of Cr (VI). MXene/PEI modified sodium
300 alginate aerogel efficiently adsorbed the Cr (VI) with adsorption potential of 538.97 mg/g. The
301 pseudo-second-order kinetic and Langmuir isotherm was followed. The composite strength was
302 enhanced due to polymeric alginate and PEI. And composite showed efficiency uptill five cycles
303 (Feng et al., 2021). Recently imidazole-MXene composite ($Ti_3C_2$@IMIZ) were fabricated and it
304 was used to remove Cr(VI) from medium. During adsorption, the Cr (VI) was converted to Cr (III)
305 and removed through physical adsorption phenomena (electrostatic force of interaction). The
306 composite was reproduce after use (Figure 7) (Yang et al., 2021) (Table 1). From reported work,
307 it can be easily concluded that MXene composites are more suitable and efficient for removal of
308 heavy metals in comparison of pristine MXenes.




309

310 **Figure 5:** Schematic illustration of the preparation of $Ti_3C_2/TiO_2$ composite. Adapted and reproduced with permission

311 (Wang et al., 2020a).




312

313 **Figure 6:** Amino-functionalized MXenes for efficient removal of Cr(VI) (Kong et al., 2021)

314

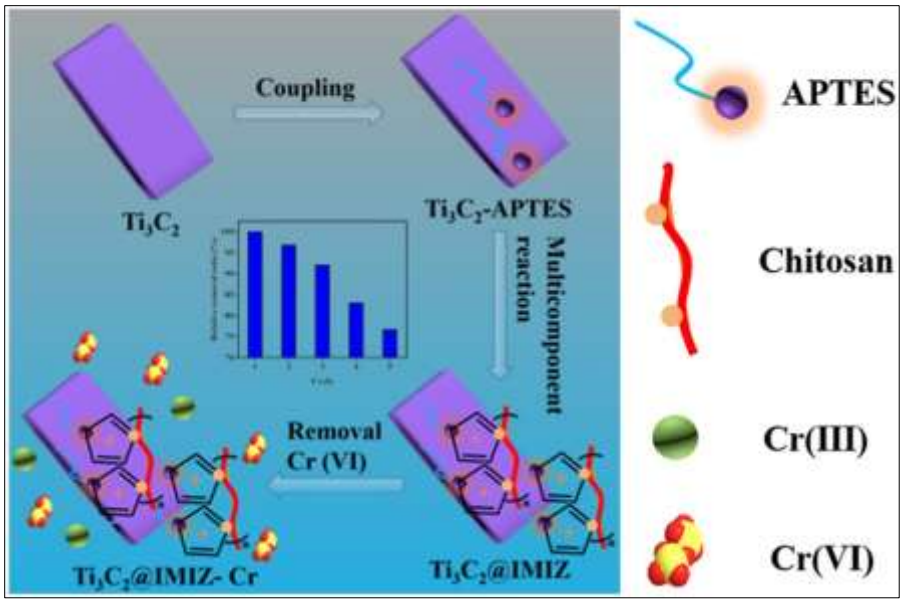


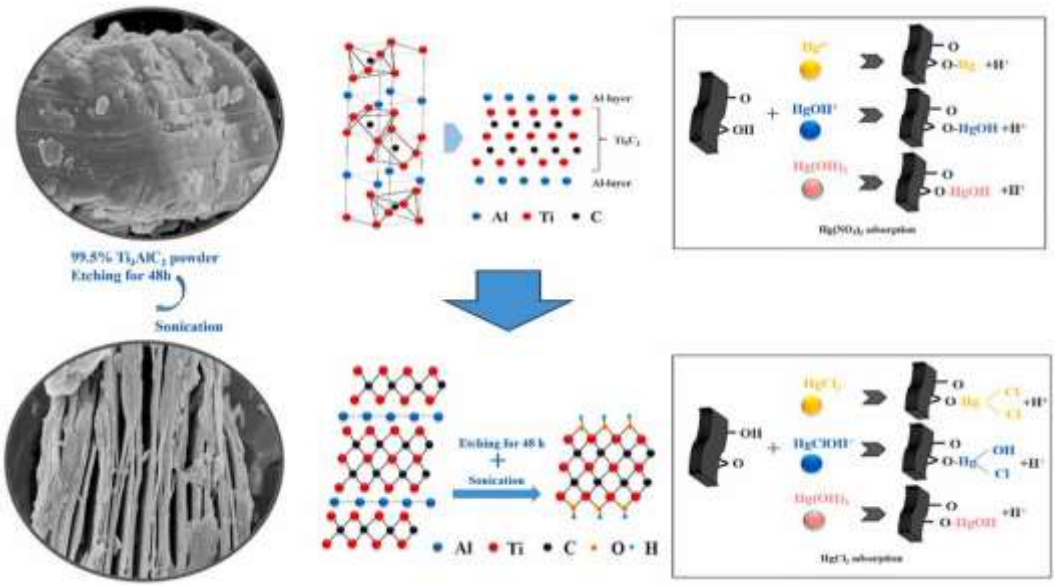

**Figure 7:** Synthesis and efficiency of Ti3C2@IMIZ for adsorptive removal of Cr(VI) (Yang et al., 2021)

### 4.3. Removal of Mercury by MXene and MXene based composites

Mercury pollution occurs due to burning of coal, waste materials. Various industries (cement, paper and mining) are also responsible for mercury pollution. Mercury ions accumulate in human body and cause severe health problems. Various studies have been conducted for removal of mercury by using MXene base materials. In a study modified MXene flakes were used to adsorb Hg (II) at different pH conditions. MXene flakes adsorbed the Hg (II) with adsorption potential of 1128.41 mg/g (Shahzad et al., 2018). MXene flakes were modified by magnetizing them to enhance their stability and fast recovery. In another study compositing of MXene aerogel spheres ($Ti_3C_2T_x$) was carried out with varying concentrations of sodium alginate and this composite (MX-SA) was used for removal of mercuric ions. High porosity, surface area and oxygenated functionalities of MXene composite made it eligible to adsorb high amount of Hg(II). The MX-$SA_{4:20}$ spheres showed exceptional adsorption potential of 932.84 mg/g for Hg(II) while MX-

329 $SA_{2:20}$ also adsorbed the Hg(II) (365 mg/g). This composite showed excellent results at various pH
330 conditions (Shahzad et al., 2019). Shahzad and his colleagues fabricated the molybdenum-
331 disulfide functionalized MXenes ($MoS_2$/MX) for removal of Hg(II) ions. Synergistic effect of
332 sulfur and oxygenated MXene assisted to obtain highest adsorption of Hg ions with adsorption
333 potential of 1435.2 mg/g (Shahzad et al., 2020). This composite worked under both acidic and
334 basic media. This study exhibited that heterogenous composites can be used to remove heavy
335 metals. Fu and his colleagues employed multilayered $Ti_3C_2O_x$ MXene for removal of Hg (II) with
336 adsorption potential of 4806 mg/g (Fu et al., 2020). In another study, MXene was used to adsorb
337 Hg(II) from solutions containing mercuric nitrate and mercuric chloride. From mercuric nitrate
338 and mercuric chloride solution, 1057.3 mg/g 773.29 mg/g Hg(II) was adsorbed by MXene
339 material at temperature 30 °C (pH 5). Even at low pH values adsorption potential was maintained
340 (Figure 8) (Hu et al., 2021) (Table 1).

341




342

Figure 8: Efficiency of oxygen-containing MXene for removal of Hg(II) from solution of mercuric chloride and mercuric nitrate (Hu et al., 2021).

### 4.4. Removal of Copper Ions by MXene and MXene based composites

MXene based materials have been used for removal of copper. Exfoliated MXene nanosheets were synthesized through ultrasonication under nitrogen atmosphere. $Ti_3C_2T_x$ showed great efficacy for copper removal because of large surface area, porosity, hydrophilicity and novel structural features. The adsorption occurs at oxygenated functional moieties on surface of MXene which assists in reduction of Cu(II) ions and forming $CuO_2$, CuO species. The delaminated MXene showed adsorption capacity around 78.45 mg/g of copper (Shahzad et al., 2017). Surface oxidation of MXenes take place after and before adsorption of copper ions. Adsorption of copper was found pH dependent. As low adsorption occurs at low pH values. After completion of adsorption, the MXene flakes showed no regeneration ability. Dong and his colleagues synthesized the hydrochar-wrapped MAX based nanofiber composites. The synthesized composites showed potential for removal of copper ions (Dong et al., 2019a). Recently rutile $TiO_2$@*d*-$Ti_3C_2T_x$ hybrid has been used for adsorption of Cu (II) ions with maximum adsorption potential of 95 mg/g (Elumalai et al., 2020). Likewise MXenes ($Ti_3C_2T_X$) functionalized with levodopa (DOPA) showed higher adsorption potential of Cu (II) ions with adsorption potential of 18.36 mg/g (Gan et al., 2020). Composite of MXene with sodium alginate also achieved high adsorption of Cu (II) ions with adsorption potential of 87.6 mg/g and equilibrium was reached in 15 minutes (Dong et al., 2019b). So MXene composites may be highly valuable for removal of heavy metals in comparison of virgin MXene (Table 1).

### 4.5. Removal/Extraction of Barium by MXene and MXene based composites

Barium is a white shiny metal exist in environment in the form of different compound. It mainly presents as barium oxide, barium sulfide, barium nitrite and barium halide. The oxidation of barium produce hydrogen in water and become soluble in water species.

**Table 1: MXene and MXene based nanomaterials for removal of heavy metal ions**

| Sr # | MXene | Targeted metal | Adsorption capacity | Mechanism | References |
|---|---|---|---|---|---|
| **Removal of Lead ions** | | | | | |
| 1 | e-TACSs e-TACFs | Pb(II) | 218 mg/g, 284.9 mg/g | Adsorption | (Gu et al., 2018a) |
| 2 | $Ti_3C_2(OH/ONa)xF_{2-x}$ | Pb (II) | 140 mg/g | Adsorption | (Peng et al., 2014) |
| 3 | $Ti_3C_2T_x$ | Pb(II) | 36.6 | Adsorption | (Jun et al., 2020a) |
| 4 | MXene/alginate nanocomposite | Pb(II) | 382.7 mg/g | Adsorption | (Dong et al., 2019b) |
| **5** | $Ti_3C_2T_x$ -KH570 | Pb(II) | 147.29 | Adsorption | (Du et al., 2019) |
| **6** | Enzymatic hydrolysis lignin functionalized $Ti_2CT_X$ MXene | Pb(II) | 232.9 mg/g | Adsorption | (Wang et al., 2020b). |
| **7** | MAX@titanate | Pb(II) | 328.9 mg/g | Adsorption | (Gu et al., 2019) |
| **8** | AlkMXene-$NH_2$ | Pb(II) | 384.63 mg/g | Adsorption | (Zhang et al., 2020) |
| **Removal of chromium ions** | | | | | |
| **9** | $Ti_3C_2T_x$ MXene nanosheets | Cr (VI) | 104 mg/g | Adsorption | (Karthikeyan et al., 2021) |
| **10** | $NH_2$-$Ti_3C_2T_x$ | Cr (VI) | 107.4 mg/g | Adsorption | (Kong et al., 2021) |
| **11** | nZVI-Alk-$Ti_3C_2$ composites | Cr (VI) | 194.87 mg/g | Adsorption | (He et al., 2020) |
| **12** | MXene | Cr (VI) | 273.1 | Adsorption | (Khan et al., 2021) |
| **13** | δ-$MnO_2$/MXene | Cr (VI) | 353.87 mg/g | Adsorption | (Khan et al., 2021) |

| | | | | | |
|---|---|---|---|---|---|
| **14** | MXene/PEI modified sodium alginate aerogel | Cr (VI) | 538.97 mg/g | Adsorption | (Feng et al., 2021) |
| **15** | MXenes/$TiO_2$ | Cr (VI) | 49.67 mg/g | Adsorption | (Wang et al., 2020a) |
| **16** | $Ti_3C_2$ | Cr (VI) | 28.3 mg/g | Adsorption | (Tang et al., 2018) |
| **17** | $Ti_3C_2T_x$-based films | Cr (VI) | 84 mg/g | Adsorption | (Xie et al., 2019) |
| **18** | $Ti_3C_2$@IMIZ | Cr (VI) | 119.5 mg/g | Adsorption | (Yang et al., 2021) |
| **19** | $Fe_3O_4$@MXene | Cr (VI) | 70.2% | Adsorption | (Yang et al., 2020) |
| **20** | $Ti_3C_2T_x$/PmPD-5/1 | Cr (VI) | 540.47 mg/g | Reduction/adsorption | (Jin et al., 2020) |
| **Removal of mercury ions** | | | | | |
| **21** | Magnetized MXene flakes | Hg (II) | 1128.41 mg/g | Adsorption | (Shahzad et al., 2018) |
| **22** | MX-$SA_{4:20}$<br>MX-$SA_{2:20}$ | Hg(II) | 932.84 mg/g<br>365 mg/g | Adsorption | (Shahzad et al., 2019) |
| **23** | $MoS_2$/MX | Hg(II) | 1435.2 mg/g | Adsorption | (Shahzad et al., 2020). |
| **24** | $Ti_3C_2O_x$ MXene | Hg(II) | 4806 mg/g | Adsorption/reduction | (Fu et al., 2020) |
| **25** | MXene | Hg(II) | 1057.3 mg/g from mercuric nitrate and 773.29 mg/g from mercuric chloride | Adsorption | (Hu et al., 2021) |
| **Removal of copper ions** | | | | | |
| **26** | Delaminated $Ti_3C_2O_x$ MXene | Cu (II) | 78.45 mg/g | Adsorption | (Shahzad et al., 2017) |
| **27** | hydrochar-wrapped MAX based nanofibers | Cu (II) | - | Adsorption | (Dong et al., 2019a). |
| **28** | Amino acids modified MXenes ($Ti_3C_2$TX-PDOPA) | Cu (II) | 18.36 mg/g | Adsorption | (Gan et al., 2020) |
| **29** | MXene/alginate composites | Cu (II) | 87.6 mg/g | Adsorption | (Dong et al., 2019b) |

| | | | | | |
|---|---|---|---|---|---|
| **30** | $TiO_2$@*d*-$Ti_3C_2T_x$ hybrid | Cu (II) | 95 mg/g | Adsorption | (Elumalai et al., 2020) |

The compatibility with water make them spread on larger area and affect human and aquatic life (Ghaemi et al., 2011; Torab-Mostaedi et al., 2011). The limit of barium in water is set as 2 mg/L and 0.7 mg/L by USA EPA and WHO respectively (Edition, 2011). So, the presence of barium above this limit cause liver problem, increase in blood pressure, irritation in stomach, difficulty in breathing, heart rhythm change, swelling of brain, muscle weakness, kidney and heart damage and may act as a carcinogenic (Celebi et al., 2009). The main source of barium is oil and gas plants. To remove barium and its compounds, a number of method have been used include ion exchange, precipitation method, adsorption and membrane filtration (Fu and Wang, 2011; Kondash et al., 2014; Fard et al., 2016). Among them, adsorption is low cost, flexible and highly efficient method which is widely used to remove barium contaminants. A number of adsorbent have been established in this regard such as natural dolomite, chloriteillite, carbon based adsorbent, kaolinite and MXenes (Fu and Wang, 2011; Fard et al., 2016; Hadi et al., 2016). MXenes are highly efficient material with good capacity and economic benefits. In 2017 Fard and coworkers established MXene with HF solution and washed through dispersion by sonication in ethanol. The final product obtained by freeze-dried method of washed material for overnight. The MXene is synthesized by intercalation and exfoliation of titanium (III) carbide (II) ($Ti_3C_2T_x$). In order to study the barium removal, they used this MXene as an adsorbent and with adsorption capacity 9.3 mg/g with 100 % removal efficiency. The 90 % of barium was removed from the solution in first 10 min selectively as compared to other metals present in solution. This adsorption of barium occurs through physisorption mechanism as a secondary route as shown in figure 9. In addition of this, Chemisorption work as a primary route by using functional groups terminated surface with –

O, –OH and –F. These functionalities form a chemical bonding with barium ion present in solution and generate barium hydroxide and barium fluoride (Fard et al., 2017). The applications of this MXene is limited in nuclear waste due to their less capacity of barium adsorption. To this end, Mu and his coworkers enhance the surface activity and metal intercalation of ($Ti_3C_2T_x$) in order improve their adsorption capacity by the using NaOH (Mu et al., 2018). Through this treatment c-lattice parameter increased upto (2.09 nm) which improve the surface interaction affinities toward barium in solution. The functional groups anchoring at the surface shows excellent ability to absorb barium upto 46.46 mg/g. This absorption capacity is unpredictable and useful for nuclear waste management. The improvement of absorption capacity through NaOH is an efficient method. In 2020 Jun et al. further improve the absorption ability of ($Ti_3C_2T_x$) toward barium and strontium in waste water. They explain adsorption of barium via electrostatic attraction of negatively charged surface of ($Ti_3C_2T_x$). They report an adsorption capacity upto 180 mg/g of barium in solution. The evidence the adsorption of barium through inner-sphere complexation, chemisorption and chemical ion exchange mechanism by FTIR, isothermal study, kinetic study and XPS respectively. The ($Ti_3C_2T_x$) MXene adsorbent can be reused upto four cycles of adsorption and desorption (Jun et al., 2020b).


Figure 9. Schematic illustration of 2D MXene based materials for the removal of radioactive pollutants from wastewater. Reproduced with permission from (Hwang et al., 2020). Copyright 2020 Elsevier.

### 4.6. Removal of Palladium by MXene and MXene based composites

Palladium is a very versatile and useful materials in the field of electronics, catalysis, medicine, jewelry and dentistry with peculiar chemical and physical properties. The advancement in electronic device enhance the use and amount of palladium (Parodi et al., 2008; Won et al., 2014; Gupta and Diwan, 2017). The main source of palladium is from minerals, ores and waste electronic devices. It is also present in nuclear waste as Pd-107 and Pd-105 produce through the fission of uranium. This nuclear waste contains non-radioactive or less radioactive palladium (Can et al., 2013). To avoid its mixing with drinking water, Pd containing nuclear waste stored by vitrification and liquid containing Pd convert into glassy matrix. However, Pd presence in this nuclear waste can destroy vitrification and form a separate layer. In this sense, removal of Pd from nuclear waste is very important to avoid further contamination with drinking water (Abney et al.,

2014). A number of method has been employed in this direction include extraction, adsorption, precipitation and filtration (Khan et al., 2015; Mu et al., 2019). Among them, adsorption method seems to be efficient and easy due to its low cost, high efficiency and absence of organic solvents during applications. For this purpose, many adsorbents have been applied. Such as lignin, cellulose, carbon black and chitosan were used as inorganic adsorbent. They work with same principle to capture Pd from aqueous media (Kim et al., 2007; Sharma and Rajesh, 2014). Moreover, their low efficiency and high cost limited the applications. Therefore, it was required to design a new type of adsorbent with low cost and high efficiency. In this regard, transition metal carbide and carbontrides (MXene) are useful material produced by etching method. They pose good hydrophilic properties and readily available for water purification and pollutant adsorbent from environment. In 2019, Mu and his coworkers synthesized $Ti_3C_2T_x$ based MXene by treating $Ti_3AlC_2$ MAX with HF at different conditions. They synthesized this MXene for the removal of Pd from nitric acid media. The d-spacing of as synthesized MXene triggered at different temperature. As the temperature increase the d-spacing also increased. The d-spacing is directly related to adsorption ability of the material. So, MXene synthesized at 45 °C shows high adsorption power as compared to MXene synthesized at 25 °C and 35 °C. The adsorption efficiency is about 184.56 mg/g, which is higher as compare to other inorganic adsorbents due to higher surface area and d-spacing. The author concluded that the synthesis temperature has vital rule on the adsorption power of MXene (Mu et al., 2018).

### 4.7. Removal of Cesium by MXene and MXene based composites

Cesium-137 is a radioactive isotopes produced during the fission process of uranium and other radioactive metals. The fission process is largely used in nuclear defense and for the production of nuclear energy. Moreover, nuclear destruction such as Fukushima and Chernobyl also produce a

large quantity of nuclear waste in environment (Lee et al., 2017; Calì et al., 2018). As produce Cs-137 is a strong beta and gamma emitter with half-life of 30.17 years and become a major problem in nuclear waste (Tan et al., 2018). It is most harmful material due to its high mobility and solubility with water. Due to its same hydration radius with potassium it can replace potassium from human's body and move in the same way pharmacokinetically as potassium. More interestingly, it enters human and animal body through food like water, meet, fishes and plants. This addition in living organism damage the cells and cause cancer (Khan et al., 2019). In order to prevent problem caused by cesium, a number of method has been used for its safe disposal and removal from waste water and nuclear waste. This involve electrodialysis, ion exchange, solvent extraction, chemical precipitation, coagulation and membrane processing. They are less effective and non-economical as a large amount of nuclear waste is produced with the passage of time. On the other hand, adsorption is a useful technique to remove radioactive waste efficiently (Yang et al., 2018). In this direction, newly developed 2D transition metal carbide and nitrides has been employed as adsorbent for nuclear waste (Lei et al., 2015). Khan and his coworkers study the use of $Ti_3C_2T_x$ as a collector of Cs+ ion from contaminated water through ingestion test. They study the adsorption of cesium in this MXene through Langmuir and Freundlich isotherm. This adsorbent shows maximum adsorption capacity up to 25.4 mg/g as a coherent with Freundlich isotherm. This adsorption capacity obtained in one minute at room temperature. The heterogeneity of the surface with hydroxyl, fluorine and oxygen groups and multilayer adsorption phenomenon of adsorbent revealed in this work. The adsorption mechanism based on the attachment of Cs ion at the interlayer space and pores of adsorbent in the presence of other ion like ($Na^+$, $Li^+$, $K^+$, $Sr^{2+}$ and $Mg^{2+}$) (Khan et al., 2019). More recently, Jun and coworkers employed adsorption test by using $Ti_3C_2T_x$ MXene for the removal of radioactive isotopes like Cs-137 from nuclear waste and

compared the result with activated carbon as an adsorbent. They noticed that the adsorption ability of MXene was about 148 mg/g for $Cs^+$ ion as compared to porous carbon shows 80 mg/g. Although porous carbon has 47 times higher surface area as compared to MXene still have less adsorption capacity. This higher adsorption ability of MXene is due to higher negatively charged surface, which shows that, electrostatic interaction plays vital role for the adsorption of $Cs^+$ ion. In addition of electrostatic force among adsorbent and $Cs^+$ ion, ion exchange mechanism also involved with presence of other cation like ($K^+$, $Na^+$, $Ca^{2+}$, and $Mg^{2+}$) and organic acid (Jun et al., 2020b).

### 4.8. Removal of Uranium ($U^{6+}$) by MXene and MXene based composites

Uranium is one of the main constituent of nuclear fuel and contaminated the environment with half-life $4.47 \times 10^9$ years. It can mix with soil and water during nuclear waste management, mining and reprocessing of nuclear fuel (Yusan and Akyil, 2008; Stewart et al., 2010). There are two main component of uranium present as toxicant $U^{4+}$ and $U^{6+}$ ions. Among them $U^{6+}$ ion greatly affect the environment due to its high solubility in water and high mobility (Schnug and Lottermoser, 2013; Pidchenko et al., 2017). To reduce $U^{6+}$ ion in aqueous media different type of sorbent has been used include nanoporous polymer, hydrothermal carbon, zeolites, metal oxides and hydroxides, metal phosphates, graphene oxide and its derivative, metal chalcogen, metal organic frameworks, clays and covalent organic framework (Yang et al., 2014; Bai et al., 2015; Lee et al., 2015; Li et al., 2015; Wang et al., 2018). Another way to reduce $U^{6+}$ from aqueous media is to convert it from highly soluble $U^{+6}$ to sparingly soluble $U^{4+}$ (O'Loughlin et al., 2003; Sun et al., 2014) through bacteria, iron sulfide, chemical reductants, zerovalent materials, magnetite and soluble iron material have been investigated. To remove this radioactive waste more efficiently, two dimensional metal carbides and carbontrides known as MXene having permeable reactive barrier, good stability, high removal tendency and good tolerance have been employed (Ghidiu et

al., 2014; Anasori et al., 2017). In contrast with others adsorbent MXenes have hydrophilic nature, charged surface, good ion exchange ability, good resistant towards acids and flexible swelling. These characteristics make them attractive candidates for management of environmental toxic materials. A number of reports have been published in the recent years about the removal of $U^{6+}$ ion by using titanium carbide, chromium carbide and vanadium carbide have been investigated extensively. These MXene are used as batch, theoretical and spectroscopic techniques (Wang et al., 2017; Deng et al., 2019; Fan et al., 2019; Wang et al., 2020b; Zhang and Liu, 2020). Among them titanium carbide shows maximum removal capacity about 470 mg/g due to surface complexation with good electrostatic attraction toward $U^{6+}$ ion as compare to vanadium carbide MXene (174 mg/g). Similarly, strong ion exchange ability of titanium based MXene also responsible for uranium uptake. This titanium based MXene also used in the form composites with good reproduction of $U^{6+}$ ion after conversion to $U^{4+}$ ion. The amidoxime group present in MXene also responsible for uranium removal through coordination with uranyl group and established a bidentate chelating complexes. These all peculiar properties of titanium based MXenes make them excellent absorbent for the removal of $U^{6+}$ ion from nuclear waste. Zhang and his coworkers measured uranyl adsorption of hydroxyl functionalized titanium carbide about 595.3 mg/g through density functional theory. They proposed that uranyl ions attach with deprotonated oxygen rather than protonated oxygen at the surface of MXene in the form of hydroxy group (Zhang et al., 2016). They reported hydrogen bonding as a dominant factor in uranium ion adsorption. On the other hand, adsorption at vanadium carbide MXene is due to -OH, -O, -F groups. Similarly, Wang and his group reduce the radionuclide waste by converting highly soluble $U^{6+}$ into partially soluble $U^{+4}$. This removal based on sorption-reduction mechanism with uptake ability 470 mg/g (Wang et al., 2018). Deng et al. established a novel heterostructures $Ti_3C_2/SrTiO_3$ based MXene through

514 oxidation of superficial layer of titanium carbide precursor (Deng et al., 2019). They used this
515 MXene on the base of photocatalytic mechanism for the removal of uranium as its oxides.

516 **5. Limitations of MXenes and MXene based composites Regarding Toxic Metal Removal**

517 Despite significant advancements in MXene production, there are a number of drawbacks to using
518 MXenes for the remediation of harmful metals from wastewater, including lower biocompatibility
519 and durability, inappropriate reusability as well as great affinity for aggregation (Ihsanullah, 2020).
520 Furthermore, rational MXene synthesis with controllable and well-defined surface chemistry
521 continue to be a major challenge. There are more than 30 kinds of reported MXenes based
522 compounds, majority of them were predicted theoretically, thus more effort is needed to
523 functionalize and synthesize different varieties of MXene that are well suited for the experimental
524 treatment of wastewater. Likewise, the biocompatibility and cytotoxicity of MXenes should also
525 be investigated prior to use as a wastewater treatment material. Noticeably, water purification
526 research concentrated solely on $Ti_3C_2T_x$ (T = OH, F, and O), with little attention paid to other
527 MXenes. On the other hand, $Ti_3C_2T_x$ MXene holds trifling interlayer arrangement and have a
528 tendency to restack in aqueous environment, which restrict its extensive use in eradicating toxic
529 metals with great hydrated ionic radii. The surface accessibility, reusability, and stability of other
530 MXenes and $Ti_3C_2T_x$ for remediation of lethal metals from wastewater can easily be upgraded
531 considerably through recombination with carbon derived materials having unique physiochemical
532 characters and greater surface area as well as abundant, cheaper, and stable polymers (Jlassi et al.,
533 2020; Xu et al., 2020). Moreover, the extensive research is yet to be needed related to the use of
534 MXene nano-architectures in eliminating hazardous contaminants and toxic metals from raw
535 wastewater. Also, there must be a detailed comparison between MXenes and other adsorbents such
536 as graphene, nanomaterials, metal-organic frameworks (MOFs), covalent organic frameworks

(COFs)and carbon nanotubes etc. to have a clear and broader idea about their roles as removal agents from wastewater.

## 6. Conclusions and Future Prospects

MXenes are among the most promising 2D layered nano-architectures currently being researched for the remediation of various hazardous environmental pollutants applications, particularly for the heavy metals. In conclusion, we have covered the essentials of MXenes, including their preparation, characteristics and their extensive characterization. Further, the current advancement in the area of environmental remediation for the removal of heavy metals along with their limitations and drawbacks has been discussed. MXenes have been found to have good metals/heavy metals removal capabilities, and their effectiveness appears to be superior to that of other traditionally used 2D materials and other pollutant adsorbents. Undoubtedly, MXenes have emerged as prospective materials for the removal of metals/heavy metals, there are still a number of impediments to overwhelmed and many questions to be answered before they can be used in the field.

1. The number of experimentally documented MXenes are limited as compared to the one which are reported through computations/simulations. Except, $Ti_3C_2T_x$ which is extensively been used as a promising candidate for the environmental remediation of organic dyes, heavy metals and other pollutants of the emerging concern, there are a number of MXenes based nano-architectures which are expected to play an emerging role for the purpose. It's important to explore and experimentally synthesize variety of MXenes with adequate functionalization, required physiochemical characteristics, high water stability, and high absorbability for further advancement in environmental remediation. Further, the area of major concern to construct MXenes based materials for environmental remediation should be the structural features such as, Hierarchical and

non-layered carbides as well as the exposure of the active metal component. This will be a challenging task to accomplish. Beyond flat films, various morphologies of MXenes, such as nanocages and nanotubes should also be an area of worth investigations for environmental applications. Also, the surface functionalities play key role in elucidating the adsorption ability of MXenes. In comparison to real-time production, the majority of the theoretical models and modeling were done on the assumption that the MXenes have uniform functionalities at the terminals. To acquire full insights into the prediction of experimental circumstances, precursors used to create designed MXenes with desired functional groups, and target pollutants, finite element modeling theoretical simulations and classical MD are extremely essential.

2. The adsorption of metals/heavy metals with hydrated ionic radii bigger than the d-spacing between the MXene sheets is limited by the restacking and narrow interlayer spacing of pristine MXenes. To encapsulate the metals/heavy metals, having bigger hydrated radii, this interlayer spacing can easily be adjusted by the introduction of some cross-linker or intercalants. This can easily enhance the adsorption capacity of MXenes.

3. It's worth noting that the delamination conditions and surface functionalities are important factors in determining MXenes' adsorption capabilities. Normally, MXenes produced by synthetic methods are functionalized with several termination groups randomly. As a result, developing synthetic techniques and post-treatments is critical in order to establish a homogenous functional group, which is a challenging problem. More crucially, due to the strong reactivity of the surface metal atoms, it is believed that metals/heavy metals removal utilizing non-terminated MXenes including surface metal atoms will be successful, this should be experimentally examined for adsorption applications. As HF is used as an etching agent for the preparation of number of MXenes so, to develop a fluorine free strategy, which is another challenging factor to be addressed.

583 Till now, the most widely exploited methodology for the fabrication of MXenes is top-down
584 method. This technique lacks in controlling the surface termination feature, which is most
585 important parameter in finding the adsorption/removal ability of the synthesized material. This
586 necessitates the development of bottom-up approach to synthesize the MXenes of desirable
587 features

588 4. Given the rapid use and increasing quantity of MXene based materials, the acute toxicity of
589 MXenes and their possible environmental risks should be thoroughly investigated. More study is
590 needed to expand the spectrum of uses for environmentally benign MXenes in environmental
591 remediation. To address the challenges and practical applicability concerning the environmental
592 remediation, the competitive cost comparison between MXenes and other 2D adsorbents like
593 graphene should be considered. Therefore, cheaper synthetic methodologies and MAX phase
594 precursors should be taken into account. Hence, MXenes composed of naturally profuse elements
595 are commended for accomplishing cost-effective environmental applications.

596 5. MXenes can easily be oxidized in the presence of water and degrade under different conditions.
597 Therefore, the evaluation of different solvents towards their stability must be addressed with due
598 care. The introduction of the MXenes to the polymeric matrices can be an option to increase the
599 stability for future environmental applications. Furthermore, the desired functionalities can also be
600 achieved by modifying the surface and manipulating the interlayer spacing via delamination and
601 intercalation.

602 6. After adsorption it is really tedious to separate the MXenes from the solution, which limit them
603 in-field practical utility for the separation of metals/heavy metals from the greater volume of
604 solutions. MXenes can be incorporated into fibers or MXene derived composites having magnetic
605 nano-architectures can be used to overcome this problem.

Conclusively, it is pertinent to say that this novel family of 2D materials has immense potential as adsorbents for the removal of metals/heavy metals. We believe that this study will provide a thorough overview of current research on the metals/heavy metals removal application of MXenes, as well as a significant push to further improve these systems for future environmental remediation research, particularly in the area of metals/heavy metals removal.

## Acknowledgment

The authors sincerely appreciate funding from Researchers Supporting Project number (RSP-2021/399), King Saud University, Riyadh, Saudi Arabia

## Conflict of interest disclosure

The representative authors have no conflict of interest to disclose in ant capacity, either competing or financial.

## References

Abney, C.W., Taylor-Pashow, K.M., Russell, S.R., Chen, Y., Samantaray, R., Lockard, J.V., Lin, W., 2014. Topotactic transformations of metal–organic frameworks to highly porous and stable inorganic sorbents for efficient radionuclide sequestration. Chemistry of Materials 26, 5231-5243.

Ahmad, R., Mirza, A., 2018. Facile one pot green synthesis of Chitosan-Iron oxide (CS-Fe2O3) nanocomposite: Removal of Pb(II) and Cd(II) from synthetic and industrial wastewater. Journal of Cleaner Production 186, 342-352.

Ahmadijokani, F., Tajahmadi, S., Bahi, A., Molavi, H., Rezakazemi, M., Ko, F., Aminabhavi, T.M., Arjmand, M., 2021. Ethylenediamine-functionalized Zr-based MOF for efficient removal of heavy metal ions from water. Chemosphere 264, 128466.

Alhabeb, M., Maleski, K., Anasori, B., Lelyukh, P., Clark, L., Sin, S., Gogotsi, Y., 2017. Guidelines for synthesis and processing of two-dimensional titanium carbide (Ti3C2T x MXene). Chemistry of Materials 29, 7633-7644.

Almeida, J.C., Cardoso, C.E., Tavares, D.S., Freitas, R., Trindade, T., Vale, C., Pereira, E., 2019. Chromium removal from contaminated waters using nanomaterials–a review. TrAC Trends in Analytical Chemistry 118, 277-291.

Anasori, B., Gogotsi, Y., 2019. Introduction to 2D transition metal carbides and nitrides (MXenes). 2D Metal carbides and nitrides (MXenes). Springer, pp. 3-12.

Anasori, B., Lukatskaya, M.R., Gogotsi, Y., 2017. 2D metal carbides and nitrides (MXenes) for energy storage. Nature Reviews Materials 2, 1-17.

637 Atkovska, K., Lisichkov, K., Ruseska, G., Dimitrov, A.T., Grozdanov, A., 2018. REMOVAL OF HEAVY METAL
638 IONS FROM WASTEWATER USING CONVENTIONAL AND NANOSORBENTS: A REVIEW. Journal of
639 Chemical Technology & Metallurgy 53.
640 Bai, Z.-Q., Yuan, L.-Y., Zhu, L., Liu, Z.-R., Chu, S.-Q., Zheng, L.-R., Zhang, J., Chai, Z.-F., Shi, W.-Q., 2015.
641 Introduction of amino groups into acid-resistant MOFs for enhanced U (VI) sorption. Journal of Materials
642 Chemistry A 3, 525-534.
643 Berrios, M., Martin, M.A., Martin, A., 2012. Treatment of pollutants in wastewater: Adsorption of
644 methylene blue onto olive-based activated carbon. Journal of Industrial and Engineering Chemistry 18,
645 780-784.
646 Bhojwani, S., Topolski, K., Mukherjee, R., Sengupta, D., El-Halwagi, M.M., 2019. Technology review and
647 data analysis for cost assessment of water treatment systems. Science of the Total Environment 651,
648 2749-2761.
649 Burakov, A.E., Galunin, E.V., Burakova, I.V., Kucherova, A.E., Agarwal, S., Tkachev, A.G., Gupta, V.K.,
650 2018. Adsorption of heavy metals on conventional and nanostructured materials for wastewater
651 treatment purposes: A review. Ecotoxicology and environmental safety 148, 702-712.
652 Burkhard, R., Deletic, A., Craig, A., 2000. Techniques for water and wastewater management: a review of
653 techniques and their integration in planning. Urban water 2, 197-221.
654 Calì, E., Qi, J., Preedy, O., Chen, S., Boldrin, D., Branford, W., Vandeperre, L., Ryan, M., 2018.
655 Functionalised magnetic nanoparticles for uranium adsorption with ultra-high capacity and selectivity.
656 Journal of Materials Chemistry A 6, 3063-3073.
657 Can, M., Bulut, E., Örnek, A., Özacar, M., 2013. Synthesis and characterization of valonea tannin resin
658 and its interaction with palladium (II), rhodium (III) chloro complexes. Chemical engineering journal 221,
659 146-158.
660 Celebi, O., Kilikli, A., Erten, H., 2009. Sorption of radioactive cesium and barium ions onto solid humic
661 acid. Journal of hazardous materials 168, 695-703.
662 Cheng, K., Cai, Z., Fu, J., Sun, X., Sun, W., Chen, L., Zhang, D., Liu, W., 2019. Synergistic adsorption of Cu
663 (II) and photocatalytic degradation of phenanthrene by a jaboticaba-like TiO2/titanate nanotube
664 composite: An experimental and theoretical study. Chemical Engineering Journal 358, 1155-1165.
665 Ciou, J.H., Li, S., Lee, P.S., 2019. Ti3C2 MXene paper for the effective adsorption and controllable release
666 of aroma molecules. Small 15, 1903281.
667 Deng, H., Li, Z.-j., Wang, L., Yuan, L.-y., Lan, J.-h., Chang, Z.-y., Chai, Z.-f., Shi, W.-q., 2019. Nanolayered
668 Ti3C2 and SrTiO3 composites for photocatalytic reduction and removal of uranium (VI). ACS Applied
669 Nano Materials 2, 2283-2294.
670 Dias, E.M., Petit, C., 2016. Correction: Towards the use of metal–organic frameworks for water reuse: a
671 review of the recent advances in the field of organic pollutants removal and degradation and the next
672 steps in the field. Journal of Materials Chemistry A 4, 3565-3565.
673 Dong, X., Wang, Y., Jia, M., Niu, Z., Cai, J., Yu, X., Ke, X., Yao, J., Zhang, X., 2019a. Sustainable and scalable
674 in-situ synthesis of hydrochar-wrapped Ti3AlC2-derived nanofibers as adsorbents to remove heavy
675 metals. Bioresource technology 282, 222-227.
676 Dong, Y., Sang, D., He, C., Sheng, X., Lei, L., 2019b. Mxene/alginate composites for lead and copper ion
677 removal from aqueous solutions. RSC advances 9, 29015-29022.
678 Du, Y., Yu, B., Wei, L., Wang, Y., Zhang, X., Ye, S., 2019. Efficient removal of Pb(II) by Ti3C2Tx powder
679 modified with a silane coupling agent. Journal of Materials Science 54, 13283-13297.
680 Edition, F., 2011. Guidelines for drinking-water quality. WHO chronicle 38, 104-108.
681 Elumalai, S., Yoshimura, M., Ogawa, M., 2020. Simultaneous Delamination and Rutile Formation on the
682 Surface of Ti3C2Tx MXene for Copper Adsorption. Chemistry – An Asian Journal 15, 1044-1051.
683 Fan, M., Wang, L., Pei, C.-X., 2019. Alkalization intercalation of MXene for electrochemical detection of
684 uranyl ion. JOURNAL OF INORGANIC MATERIALS-BEIJING- 34, 85-90.

685 Fard, A.K., Mckay, G., Chamoun, R., Rhadfi, T., Preud'Homme, H., Atieh, M.A., 2017. Barium removal
686 from synthetic natural and produced water using MXene as two dimensional (2-D) nanosheet
687 adsorbent. Chemical engineering journal 317, 331-342.
688 Fard, A.K., Rhadfi, T., Khraisheh, M., Atieh, M.A., Khraisheh, M., Hilal, N., 2016. Reducing flux decline and
689 fouling of direct contact membrane distillation by utilizing thermal brine from MSF desalination plant.
690 Desalination 379, 172-181.
691 Feng, Y., Wang, H., Xu, J., Du, X., Cheng, X., Du, Z., Wang, H., 2021. Fabrication of MXene/PEI
692 functionalized sodium alginate aerogel and its excellent adsorption behavior for Cr(VI) and Congo Red
693 from aqueous solution. Journal of Hazardous Materials 416, 125777.
694 Fu, F., Wang, Q., 2011. Removal of heavy metal ions from wastewaters: a review. Journal of
695 environmental management 92, 407-418.
696 Fu, K., Liu, X., Yu, D., Luo, J., Wang, Z., Crittenden, J.C., 2020. Highly Efficient and Selective Hg(II) Removal
697 from Water Using Multilayered Ti3C2Ox MXene via Adsorption Coupled with Catalytic Reduction
698 Mechanism. Environmental Science & Technology 54, 16212-16220.
699 Fu, L., Yan, Z., Zhao, Q., Yang, H., 2018. Novel 2D nanosheets with potential applications in heavy metal
700 purification: A review. Advanced Materials Interfaces 5, 1801094.
701 Gan, D., Huang, Q., Dou, J., Huang, H., Chen, J., Liu, M., Wen, Y., Yang, Z., Zhang, X., Wei, Y., 2020.
702 Bioinspired functionalization of MXenes (Ti3C2TX) with amino acids for efficient removal of heavy metal
703 ions. Applied Surface Science 504, 144603.
704 Gao, G., Ding, G., Li, J., Yao, K., Wu, M., Qian, M., 2016. Monolayer MXenes: promising half-metals and
705 spin gapless semiconductors. Nanoscale 8, 8986-8994.
706 Ghaemi, A., Torab-Mostaedi, M., Ghannadi-Maragheh, M., 2011. Characterizations of strontium (II) and
707 barium (II) adsorption from aqueous solutions using dolomite powder. Journal of Hazardous Materials
708 190, 916-921.
709 Ghasemi, Z., Seif, A., Ahmadi, T.S., Zargar, B., Rashidi, F., Rouzbahani, G.M., 2012. Thermodynamic and
710 kinetic studies for the adsorption of Hg (II) by nano-TiO2 from aqueous solution. Advanced Powder
711 Technology 23, 148-156.
712 Ghidiu, M., Lukatskaya, M.R., Zhao, M.-Q., Gogotsi, Y., Barsoum, M.W., 2014. Conductive two-
713 dimensional titanium carbide 'clay'with high volumetric capacitance. Nature 516, 78-81.
714 Giammar, D.E., Maus, C.J., Xie, L., 2007. Effects of particle size and crystalline phase on lead adsorption
715 to titanium dioxide nanoparticles. Environmental Engineering Science 24, 85-95.
716 Gu, P., Xing, J., Wen, T., Zhang, R., Wang, J., Zhao, G., Hayat, T., Ai, Y., Lin, Z., Wang, X., 2018a.
717 Experimental and theoretical calculation investigation on efficient Pb (II) adsorption on etched Ti 3 AlC 2
718 nanofibers and nanosheets. Environmental Science: Nano 5, 946-955.
719 Gu, P., Xing, J., Wen, T., Zhang, R., Wang, J., Zhao, G., Hayat, T., Ai, Y., Lin, Z., Wang, X., 2018b.
720 Experimental and theoretical calculation investigation on efficient Pb(ii) adsorption on etched Ti3AlC2
721 nanofibers and nanosheets. Environmental Science: Nano 5, 946-955.
722 Gu, P., Zhang, S., Zhang, C., Wang, X., Khan, A., Wen, T., Hu, B., Alsaedi, A., Hayat, T., Wang, X., 2019.
723 Two-dimensional MAX-derived titanate nanostructures for efficient removal of Pb(ii). Dalton
724 Transactions 48, 2100-2107.
725 Gupta, P., Diwan, B., 2017. Bacterial exopolysaccharide mediated heavy metal removal: a review on
726 biosynthesis, mechanism and remediation strategies. Biotechnology Reports 13, 58-71.
727 Habib, I., Ferrer, P., Ray, S.C., Ozoemena, K.I., 2019. Interrogating the impact of onion-like carbons on
728 the supercapacitive properties of MXene (Ti2CTX). Journal of Applied Physics 126, 134301.
729 Hadi, P., Ning, C., Kubicki, J.D., Mueller, K., Fagan, J.W., Luo, Z., Weng, L., McKay, G., 2016. Sustainable
730 development of a surface-functionalized mesoporous aluminosilicate with ultra-high ion exchange
731 efficiency. Inorganic Chemistry Frontiers 3, 502-513.

He, L., Huang, D., He, Z., Yang, X., Yue, G., Zhu, J., Astruc, D., Zhao, P., 2020. Nanoscale zero-valent iron intercalated 2D titanium carbides for removal of Cr(VI) in aqueous solution and the mechanistic aspect. Journal of Hazardous Materials 388, 121761.
Hu, Q., Sun, D., Wu, Q., Wang, H., Wang, L., Liu, B., Zhou, A., He, J., 2013. MXene: a new family of promising hydrogen storage medium. The Journal of Physical Chemistry A 117, 14253-14260.
Hu, X., Chen, C., Zhang, D., Xue, Y., 2021. Kinetics, isotherm and chemical speciation analysis of Hg(Ⅱ) adsorption over oxygen-containing MXene adsorbent. Chemosphere 278, 130206.
Hwang, S.K., Kang, S.-M., Rethinasabapathy, M., Roh, C., Huh, Y.S., 2020. MXene: An emerging two-dimensional layered material for removal of radioactive pollutants. Chemical Engineering Journal 397, 125428.
Ihsanullah, I., 2020. MXenes (two-dimensional metal carbides) as emerging nanomaterials for water purification: Progress, challenges and prospects. Chemical Engineering Journal 388, 124340.
Ijanu, E., Kamaruddin, M., Norashiddin, F., 2020. Coffee processing wastewater treatment: a critical review on current treatment technologies with a proposed alternative. Applied Water Science 10, 1-11.
Jasper, J.T., Yang, Y., Hoffmann, M.R., 2017. Toxic byproduct formation during electrochemical treatment of latrine wastewater. Environmental science & technology 51, 7111-7119.
Jin, L., Chai, L., Yang, W., Wang, H., Zhang, L., 2020. Two-dimensional titanium carbides (Ti3C2Tx) functionalized by poly (m-phenylenediamine) for efficient adsorption and reduction of hexavalent chromium. International journal of environmental research and public health 17, 167.
Jlassi, K., Eid, K., Sliem, M.H., Abdullah, A.M., Chehimi, M.M., Krupa, I., 2020. Rational synthesis, characterization, and application of environmentally friendly (polymer–carbon dot) hybrid composite film for fast and efficient UV-assisted Cd 2+ removal from water. Environmental Sciences Europe 32, 1-13.
Jun, B.-M., Her, N., Park, C.M., Yoon, Y., 2020a. Effective removal of Pb (ii) from synthetic wastewater using Ti 3 C 2 T x MXene. Environmental Science: Water Research & Technology 6, 173-180.
Jun, B.-M., Park, C.M., Heo, J., Yoon, Y., 2020b. Adsorption of Ba2+ and Sr2+ on Ti3C2Tx MXene in model fracking wastewater. Journal of environmental management 256, 109940.
Karaçetin, G., Sivrikaya, S., Imamoğlu, M., 2014. Adsorption of methylene blue from aqueous solutions by activated carbon prepared from hazelnut husk using zinc chloride. Journal of Analytical and Applied Pyrolysis 110, 270-276.
Karthikeyan, P., Ramkumar, K., Pandi, K., Fayyaz, A., Meenakshi, S., Park, C.M., 2021. Effective removal of Cr(VI) and methyl orange from the aqueous environment using two-dimensional (2D) Ti3C2Tx MXene nanosheets. Ceramics International 47, 3692-3698.
Khan, A.R., Awan, S.K., Husnain, S.M., Abbas, N., Anjum, D.H., Abbas, N., Benaissa, M., Mirza, C.R., Mujtaba-ul-Hassan, S., Shahzad, F., 2021. 3D flower like δ-MnO2/MXene Nano-hybrids for the removal of hexavalent Cr from wastewater. Ceramics International.
Khan, A.R., Husnain, S.M., Shahzad, F., Mujtaba-ul-Hassan, S., Mehmood, M., Ahmad, J., Mehran, M.T., Rahman, S., 2019. Two-dimensional transition metal carbide (Ti 3 C 2 T x) as an efficient adsorbent to remove cesium (Cs+). Dalton Transactions 48, 11803-11812.
Khan, T.A., Chaudhry, S.A., Ali, I., 2015. Equilibrium uptake, isotherm and kinetic studies of Cd (II) adsorption onto iron oxide activated red mud from aqueous solution. Journal of Molecular Liquids 202, 165-175.
Kim, Y.-H., Ogata, T., Nakano, Y., 2007. Kinetic analysis of palladium (II) adsorption process on condensed-tannin gel based on redox reaction models. Water research 41, 3043-3050.
Kondash, A.J., Warner, N.R., Lahav, O., Vengosh, A., 2014. Radium and barium removal through blending hydraulic fracturing fluids with acid mine drainage. Environmental science & technology 48, 1334-1342.

Kong, A., Sun, Y., Peng, M., Gu, H., Fu, Y., Zhang, J., Li, W., 2021. Amino-functionalized MXenes for efficient removal of Cr(VI). Colloids and Surfaces A: Physicochemical and Engineering Aspects 617, 126388.
Lee, H.Y., Kim, H.S., Jeong, H.-K., Park, M., Chung, D.-Y., Lee, K.-Y., Lee, E.-H., Lim, W.T., 2017. Selective removal of radioactive cesium from nuclear waste by zeolites: on the origin of cesium selectivity revealed by systematic crystallographic studies. The Journal of Physical Chemistry C 121, 10594-10608.
Lee, S.S., Li, W., Kim, C., Cho, M., Lafferty, B.J., Fortner, J.D., 2015. Surface functionalized manganese ferrite nanocrystals for enhanced uranium sorption and separation in water. Journal of Materials Chemistry A 3, 21930-21939.
Lei, J.-C., Zhang, X., Zhou, Z., 2015. Recent advances in MXene: Preparation, properties, and applications. Frontiers of Physics 10, 276-286.
Li, J., Yang, X., Bai, C., Tian, Y., Li, B., Zhang, S., Yang, X., Ding, S., Xia, C., Tan, X., 2015. A novel benzimidazole-functionalized 2-D COF material: Synthesis and application as a selective solid-phase extractant for separation of uranium. Journal of colloid and interface science 437, 211-218.
Lim, J.Y., Mubarak, N., Abdullah, E., Nizamuddin, S., Khalid, M., 2018. Recent trends in the synthesis of graphene and graphene oxide based nanomaterials for removal of heavy metals—A review. Journal of Industrial and Engineering Chemistry 66, 29-44.
Melchior, S.A., Palaniyandy, N., Sigalas, I., Iyuke, S.E., Ozoemena, K.I., 2019. Probing the electrochemistry of MXene (Ti2CTx)/electrolytic manganese dioxide (EMD) composites as anode materials for lithium-ion batteries. Electrochimica Acta 297, 961-973.
Mirza, A., Ahmad, R., 2018. Novel recyclable (Xanthan gum/montmorillonite) bionanocomposite for the removal of Pb (II) from synthetic and industrial wastewater. Environmental Technology & Innovation 11, 241-252.
Mittal, J., Ahmad, R., Mariyam, A., Gupta, V., Mittal, A., 2021. Expeditious and enhanced sequestration of heavy metal ions from aqueous environment by papaya peel carbon: a green and low-cost adsorbent. DESALINATION AND WATER TREATMENT 210, 365-376.
Mu, W., Du, S., Li, X., Yu, Q., Wei, H., Yang, Y., Peng, S., 2019. Removal of radioactive palladium based on novel 2D titanium carbides. Chemical Engineering Journal 358, 283-290.
Mu, W., Du, S., Yu, Q., Li, X., Wei, H., Yang, Y., 2018. Improving barium ion adsorption on two-dimensional titanium carbide by surface modification. Dalton Transactions 47, 8375-8381.
Naguib, M., Come, J., Dyatkin, B., Presser, V., Taberna, P.-L., Simon, P., Barsoum, M.W., Gogotsi, Y., 2012. MXene: a promising transition metal carbide anode for lithium-ion batteries. Electrochemistry Communications 16, 61-64.
Ng, V.M.H., Huang, H., Zhou, K., Lee, P.S., Que, W., Xu, J.Z., Kong, L.B., 2017. Recent progress in layered transition metal carbides and/or nitrides (MXenes) and their composites: synthesis and applications. Journal of Materials Chemistry A 5, 3039-3068.
Ngah, W.W., Teong, L., Hanafiah, M.M., 2011. Adsorption of dyes and heavy metal ions by chitosan composites: A review. Carbohydrate polymers 83, 1446-1456.
O'Loughlin, E.J., Kelly, S.D., Cook, R.E., Csencsits, R., Kemner, K.M., 2003. Reduction of uranium (VI) by mixed iron (II)/iron (III) hydroxide (green rust): formation of UO2 nanoparticles. Environmental science & technology 37, 721-727.
Oguz, E., Keskinler, B., 2005. Determination of adsorption capacity and thermodynamic parameters of the PAC used for bomaplex red CR-L dye removal. Colloids and Surfaces A: Physicochemical and Engineering Aspects 268, 124-130.
Parodi, A., Vincent, T., Pilsniak, M., Trochimczuk, A.W., Guibal, E., 2008. Palladium and platinum binding on an imidazol containing resin. Hydrometallurgy 92, 1-10.

Peng, Q., Guo, J., Zhang, Q., Xiang, J., Liu, B., Zhou, A., Liu, R., Tian, Y., 2014. Unique lead adsorption behavior of activated hydroxyl group in two-dimensional titanium carbide. Journal of the American Chemical Society 136, 4113-4116.
Pidchenko, I., Kvashnina, K.O., Yokosawa, T., Finck, N., Bahl, S., Schild, D., Polly, R., Bohnert, E., Rossberg, A., Göttlicher, J.r., 2017. Uranium redox transformations after U (VI) coprecipitation with magnetite nanoparticles. Environmental science & technology 51, 2217-2225.
Rasool, K., Mahmoud, K.A., Johnson, D.J., Helal, M., Berdiyorov, G.R., Gogotsi, Y., 2017. Efficient antibacterial membrane based on two-dimensional Ti 3 C 2 T x (MXene) nanosheets. Scientific reports 7, 1-11.
Rasool, K., Pandey, R.P., Rasheed, P.A., Buczek, S., Gogotsi, Y., Mahmoud, K.A., 2019. Water treatment and environmental remediation applications of two-dimensional metal carbides (MXenes). Materials Today 30, 80-102.
Schnug, E., Lottermoser, B.G., 2013. Fertilizer-derived uranium and its threat to human health. ACS Publications.
Shahzad, A., Jang, J., Lim, S.-R., Lee, D.S., 2020. Unique selectivity and rapid uptake of molybdenum-disulfide-functionalized MXene nanocomposite for mercury adsorption. Environmental Research 182, 109005.
Shahzad, A., Nawaz, M., Moztahida, M., Jang, J., Tahir, K., Kim, J., Lim, Y., Vassiliadis, V.S., Woo, S.H., Lee, D.S., 2019. Ti3C2Tx MXene core-shell spheres for ultrahigh removal of mercuric ions. Chemical Engineering Journal 368, 400-408.
Shahzad, A., Rasool, K., Miran, W., Nawaz, M., Jang, J., Mahmoud, K.A., Lee, D.S., 2017. Two-Dimensional Ti3C2Tx MXene Nanosheets for Efficient Copper Removal from Water. ACS Sustainable Chemistry & Engineering 5, 11481-11488.
Shahzad, A., Rasool, K., Miran, W., Nawaz, M., Jang, J., Mahmoud, K.A., Lee, D.S., 2018. Mercuric ion capturing by recoverable titanium carbide magnetic nanocomposite. Journal of hazardous materials 344, 811-818.
Sharma, S., Rajesh, N., 2014. 2-Mercaptobenzothiazole impregnated cellulose prepared by ultrasonication for the effective adsorption of precious metal palladium. Chemical Engineering Journal 241, 112-121.
Sherlala, A., Raman, A., Bello, M., Asghar, A., 2018. A review of the applications of organo-functionalized magnetic graphene oxide nanocomposites for heavy metal adsorption. Chemosphere 193, 1004-1017.
Skouteris, G., Saroj, D., Melidis, P., Hai, F.I., Ouki, S., 2015. The effect of activated carbon addition on membrane bioreactor processes for wastewater treatment and reclamation–a critical review. Bioresource technology 185, 399-410.
Stewart, B.D., Mayes, M.A., Fendorf, S., 2010. Impact of uranyl− calcium− carbonato complexes on uranium (VI) adsorption to synthetic and natural sediments. Environmental science & technology 44, 928-934.
Sun, Y., Ding, C., Cheng, W., Wang, X., 2014. Simultaneous adsorption and reduction of U (VI) on reduced graphene oxide-supported nanoscale zerovalent iron. Journal of Hazardous Materials 280, 399-408.
Tan, X., Fang, M., Tan, L., Liu, H., Ye, X., Hayat, T., Wang, X., 2018. Core–shell hierarchical C@ Na 2 Ti 3 O 7· 9H 2 O nanostructures for the efficient removal of radionuclides. Environmental Science: Nano 5, 1140-1149.
Tang, Y., Yang, C., Que, W., 2018. A novel two-dimensional accordion-like titanium carbide (MXene) for adsorption of Cr (VI) from aqueous solution. Journal of Advanced Dielectrics 8, 1850035.
Torab-Mostaedi, M., Ghaemi, A., Ghassabzadeh, H., Ghannadi-Maragheh, M., 2011. Removal of strontium and barium from aqueous solutions by adsorption onto expanded Perlite. The Canadian journal of chemical engineering 89, 1247-1254.

Vardhan, K.H., Kumar, P.S., Panda, R.C., 2019. A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. Journal of Molecular Liquids 290, 111197.
Wang, G., Wang, X., Chai, X., Liu, J., Deng, N., 2010. Adsorption of uranium (VI) from aqueous solution on calcined and acid-activated kaolin. Applied Clay Science 47, 448-451.
Wang, H., Cui, H., Song, X., Xu, R., Wei, N., Tian, J., Niu, H., 2020a. Facile synthesis of heterojunction of MXenes/TiO2 nanoparticles towards enhanced hexavalent chromium removal. Journal of colloid and interface science 561, 46-57.
Wang, K., Zhou, Y., Xu, W., Huang, D., Wang, Z., Hong, M., 2016. Fabrication and thermal stability of two-dimensional carbide Ti3C2 nanosheets. Ceramics International 42, 8419-8424.
Wang, L., Song, H., Yuan, L., Li, Z., Zhang, Y., Gibson, J.K., Zheng, L., Chai, Z., Shi, W., 2018. Efficient U (VI) reduction and sequestration by Ti2CT x MXene. Environmental science & technology 52, 10748-10756.
Wang, L., Tao, W., Yuan, L., Liu, Z., Huang, Q., Chai, Z., Gibson, J.K., Shi, W., 2017. Rational control of the interlayer space inside two-dimensional titanium carbides for highly efficient uranium removal and imprisonment. Chemical Communications 53, 12084-12087.
Wang, S., Liu, Y., Lü, Q.-F., Zhuang, H., 2020b. Facile preparation of biosurfactant-functionalized Ti2CTX MXene nanosheets with an enhanced adsorption performance for Pb(II) ions. Journal of Molecular Liquids 297, 111810.
Won, S.W., Kotte, P., Wei, W., Lim, A., Yun, Y.-S., 2014. Biosorbents for recovery of precious metals. Bioresource technology 160, 203-212.
Wu, Y., Nie, P., Wang, J., Dou, H., Zhang, X., 2017. Few-layer MXenes delaminated via high-energy mechanical milling for enhanced sodium-ion batteries performance. ACS applied materials & interfaces 9, 39610-39617.
Wu, Y., Pang, H., Liu, Y., Wang, X., Yu, S., Fu, D., Chen, J., Wang, X., 2019. Environmental remediation of heavy metal ions by novel-nanomaterials: a review. Environmental pollution 246, 608-620.
Xie, X., Chen, C., Zhang, N., Tang, Z.-R., Jiang, J., Xu, Y.-J., 2019. Microstructure and surface control of MXene films for water purification. Nature Sustainability 2, 856-862.
Xiu, L., Wang, Z., Yu, M., Wu, X., Qiu, J., 2018. Aggregation-resistant 3D MXene-based architecture as efficient bifunctional electrocatalyst for overall water splitting. ACS nano 12, 8017-8028.
Xu, X., Yang, T., Zhang, Q., Xia, W., Ding, Z., Eid, K., Abdullah, A.M., Hossain, M.S.A., Zhang, S., Tang, J., 2020. Ultrahigh capacitive deionization performance by 3D interconnected MOF-derived nitrogen-doped carbon tubes. Chemical Engineering Journal 390, 124493.
Yang, G., Hu, X., Liang, J., Huang, Q., Dou, J., Tian, J., Deng, F., Liu, M., Zhang, X., Wei, Y., 2021. Surface functionalization of MXene with chitosan through in-situ formation of polyimidazoles and its adsorption properties. Journal of Hazardous Materials, 126220.
Yang, H.-M., Hwang, J.R., Lee, D.Y., Kim, K.B., Park, C.W., Kim, H.R., Lee, K.-W., 2018. Eco-friendly one-pot synthesis of Prussian blue-embedded magnetic hydrogel beads for the removal of cesium from water. Scientific reports 8, 1-10.
Yang, X., Li, J., Liu, J., Tian, Y., Li, B., Cao, K., Liu, S., Hou, M., Li, S., Ma, L., 2014. Simple small molecule carbon source strategy for synthesis of functional hydrothermal carbon: preparation of highly efficient uranium selective solid phase extractant. Journal of Materials Chemistry A 2, 1550-1559.
Yang, X., Liu, Y., Hu, S., Yu, F., He, Z., Zeng, G., Feng, Z., Sengupta, A., 2020. Construction of Fe3O4@ MXene composite nanofiltration membrane for heavy metal ions removal from wastewater. Polymers for Advanced Technologies.
Yang, X., Wan, Y., Zheng, Y., He, F., Yu, Z., Huang, J., Wang, H., Ok, Y.S., Jiang, Y., Gao, B., 2019. Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy metals from aqueous solutions: a critical review. Chemical Engineering Journal 366, 608-621.

Ying, Y., Liu, Y., Wang, X., Mao, Y., Cao, W., Hu, P., Peng, X., 2015. Two-dimensional titanium carbide for efficiently reductive removal of highly toxic chromium (VI) from water. ACS applied materials & interfaces 7, 1795-1803.
Yusan, S.D., Akyil, S., 2008. Sorption of uranium (VI) from aqueous solutions by akaganeite. Journal of hazardous materials 160, 388-395.
Zhang, C.J., Pinilla, S., McEvoy, N., Cullen, C.P., Anasori, B., Long, E., Park, S.-H., Seral-Ascaso, A.s., Shmeliov, A., Krishnan, D., 2017. Oxidation stability of colloidal two-dimensional titanium carbides (MXenes). Chemistry of Materials 29, 4848-4856.
Zhang, G., Wang, T., Xu, Z., Liu, M., Shen, C., Meng, Q., 2020. Synthesis of amino-functionalized Ti3C2Tx MXene by alkalization-grafting modification for efficient lead adsorption. Chemical Communications 56, 11283-11286.
Zhang, X., Liu, Y., 2020. Nanomaterials for radioactive wastewater decontamination. Environmental Science: Nano 7, 1008-1040.
Zhang, Y.-J., Lan, J.-H., Wang, L., Wu, Q.-Y., Wang, C.-Z., Bo, T., Chai, Z.-F., Shi, W.-Q., 2016. Adsorption of uranyl species on hydroxylated titanium carbide nanosheet: A first-principles study. Journal of hazardous materials 308, 402-410.
Zhang, Y., Wang, L., Zhang, N., Zhou, Z., 2018. Adsorptive environmental applications of MXene nanomaterials: a review. RSC advances 8, 19895-19905.
Zhu, H.-Y., Jiang, R., Xiao, L., 2010. Adsorption of an anionic azo dye by chitosan/kaolin/γ-Fe2O3 composites. Applied Clay Science 48, 522-526.
Zhu, M., Huang, Y., Deng, Q., Zhou, J., Pei, Z., Xue, Q., Huang, Y., Wang, Z., Li, H., Huang, Q., 2016. Highly flexible, freestanding supercapacitor electrode with enhanced performance obtained by hybridizing polypyrrole chains with MXene. Advanced Energy Materials 6, 1600969.
Zou, G., Guo, J., Peng, Q., Zhou, A., Zhang, Q., Liu, B., 2016. Synthesis of urchin-like rutile titania carbon nanocomposites by iron-facilitated phase transformation of MXene for environmental remediation. Journal of Materials Chemistry A 4, 489-499.