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Emerging Applications of Novel Nanoparticles



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Lecture Notes in Nanoscale Science and Technology (LNNST) aims to report latest developments in nanoscale science and technology research and teaching – quickly, informally and at a high level. Through publication, LNNST commits to serve the open communication of scientific and technological advances in the creation and use of objects at the nanometer scale, crossing the boundaries of physics, materials science, biology, chemistry, and engineering. Certainly, while historically the mysteries in each of the sciences have been very different, they have all required a relentless step-by-step pursuit to uncover the answer to a challenging scientific question, but recently many of the answers have brought questions that lie at the boundaries between the life sciences and the physical sciences and between what is fundamental and what is application. This is no accident since recent research in the physical and life sciences have each independently cut a path to the edge of their disciplines. As both paths intersect one may ask if transport of material in a cell is biology or is it physics? This intersection of curiosity makes us realize that nanoscience and technology crosses many if not all disciplines. It is this market that the proposed series of lecture notes targets.

Suneev Anil Bansal • Virat Khanna
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Preface

This book entitled *Emerging Applications of Novel Nanoparticles* focuses on the different types of nanomaterials, their synthesis routes, and potential application in various fields. Earlier there was a trend of using materials in micron or submicron form as they were best suited for the applications of past time. However, with the advancement of time there has been a remarkable shift in the demand of society due to which, essentially, we have to alter the type of material which was being used. Nanomaterials are the materials in which the particle size goes in a range of 1-100 nm. This improves the properties by manifold. This book lays special emphasis on 2D and Mxene nanomaterials along with their application in different fields like pollutant removal, forensics, medical and biomedical applications, etc.

This book also addresses the concern over the processing of different nanomaterials and the various challenges associated with it. Other books are also available in the related area; however, this volume specifically discusses more focused approach towards the societal applications, hence the word “Novel Nanoparticles” has been specifically added to the title of the book.

The contents of this book will be highly beneficial for the students and scholars who are currently studying different UG and PG programs in mechanical engineering, civil engineering, material science, chemistry, physics as well as researchers working in industry and academia.

Seeing the requirements of day-to-day life, this book is divided into 13 chapters:

Chapter “[2D Nanomaterials for Adsorption of Wastewater Pollutants](#)” discusses in detail about the synthesis and physicochemical properties of different 2D materials. Special emphasis has been placed on the usage of 2D-based materials and related mechanisms in the adsorption of different wastewater pollutants.

Chapter “[Unveiling the Power of Nanomaterials in the Area of Forensics](#)” is dedicated towards the usage of nanomaterials in the field of nano-sensors and nano-imaging with their application in criminal investigation. Discussion has also been held on the implementation of nanomaterials in the field of evidence analysis under forensic studies.

- Chapter “[Buckypapers: Applications in Composite Materials](#)” discusses the development of Buckypapers (BPs) by making use of densely packed carbon nanotube (CNT) thin films. CNTs show a good combination of electrical, thermal, and mechanical properties. Special emphasis has been laid down on the preparation of BPs and their physical and morphological properties along with the potential applications.
- Chapter “[Nanoparticles for Diagnosis and Treatment of Infectious Diseases](#)” highlights the application of nanomaterials in diagnosing and treating infectious diseases. Current challenges and future research possibilities for using these nanomaterials in disease management have also been discussed in the chapter.
- Chapter “[Ti₃C₂T_x Mxene Based Nanostructured Materials For Emerging Applications](#)” describes the potential of using Ti₃C₂T_x MXene as an important 2D nanomaterial. Apart from that, a special emphasis has been laid down in the chapter towards the usage of these Maxene in optoelectronic devices, such as photovoltaics, photodetectors, and photoelectrochemical devices, due to their exceptional electronic, optical, mechanical, and thermal properties.
- Chapter “[Molybdenum Disulfide: A 2D Material](#)” discusses about molybdenum disulfide, which is an important 2D material that shows unusual properties. The chapter also showcases a comprehensive investigation of the synthesis methods in addition to its structural as well as electrical properties, along with several applications.
- Chapter “[Surface Functionalization of 2D MOs for Enhanced Biocompatibility and Biomedical Applications](#)” explains about the various surface functionalization methods for developing 2D metal oxides and their applications in drug delivery, imaging, and biosensors.
- Chapter “[Application of a Novel Nanotherapeutic Strategy in Ayurvedic Treatment](#)” discusses the usage of nanomaterials in ayurvedic treatment. The chapter also illustrates the nanotherapeutic approach which improves the therapeutic strategy for treatment of acute diseases like cancer, genetic diseases, neurological diseases, etc.
- Chapter “[Biosynthesis of Iron Oxide Nanoparticles \(IONPs\): Toxicity Evaluation and Applications for Magnetic Resonance Imaging and Magnetic Hyperthermia](#)” discusses the biological synthesis and biomedical applications of iron oxide nanoparticles (IONPs). Apart from that, in the chapter, discussion has also been carried out on biosynthesized metallic nanoparticles.
- Chapter “[Effect of Annealing Temperature on Structural, Morphological and Optical Properties of CdZnTe Thin Films](#)” discusses the effect of annealing temperature on structural, morphological, and optical properties of CdZnTe thin films.
- Chapter “[Two-Dimensional Molybdenum Disulfide Nanosheets Based Optoelectronic Devices](#)” reports a detailed discussion on development and characterization of two-dimensional molybdenum disulfide nanosheets for the appli-

cation in optoelectronic devices. Apart from that, few recent developments with respect to optoelectronic devices fabricated using MoS₂ nanosheets along with various methods of synthesizing MoS₂ nanosheets and fabricating optoelectronic devices have been discussed in the chapter.

Chapter “[Photocatalytic Hydrogen Production of Perovskite Based Nanocomposites by Green Laser Irradiation Techniques](#)” illustrates the development of photocatalyst-based on a binary direct Z-scheme STCS perovskite. The recyclability effect of the developed material has also been discussed in the chapter.

Chapter “[Tuning the Physical Properties of Perovskite Multiferroic Nanoparticles for Green Energy Applications](#)” reports the detailed review of alternative methods for tuning the properties of perovskite materials. A special case study on the behavior of BiFeO₃ and transition-metal-doped BiFeO₃ is also discussed as a perovskite material in the chapter.

All the 13 chapters submitted by the different authors are written in a systematic manner thereby covering all the recent references related to the various fields of nanoparticles.

All the four editors are thankful to almighty God. Apart from this, Dr. Suneev Anil Bansal, Dr. Virat Khanna, and Dr. Nilanthi Balakrishnan are also thankful to their family members for the support extended during the period of editing of this book. Dr. Pallav Gupta is also thankful to his mother (Beena Gupta), wife (Dr. Ritu Agrahari), and son (Saahas Gupta) for the encouragement as well as support extended during the entire duration of editing this book.

We editors also thankfully acknowledge the heartfelt support received from all our contributors who submitted their chapters in this volume of the book.

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2D Nanomaterials for Adsorption of Wastewater Pollutants



Enas Amdeha, Aesha Abd El Pasir, and Diana S. Raie

Abbreviations

Symbol	Definition
2D	Two dimensional
Co	Initial Concentration
CNDs	Carbon nanodots
CVD	Chemical vapour deposition
DFT	Density Functional Theory
GO	Graphene oxide
HMI	Heavy metal ions
HTNs	Hierarchical titanite nanostructures
MB	Methylene blue
MG	Malachite Green
MO	Methyl orange
MOFs	Metal-Organic Frameworks
MoS ₂	Molybdenum disulfide
NMR	Nuclear Magnetic Resonance
NMs	Nanomaterials
NPs	Nanoparticles
PFAS	Perfluoroalkyl and polyfluoroalkyl substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane sulfonic acid

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pKa	Acid dissociation constants
Q	Adsorption capacity
rGO	Reduced graphene oxide
SSA	Specific Surface Area
T	Temperature
TGA	Thermal Gravimetric Analysis
TMDs	Transition Metal Dichalcogenides
UO ₂ ²⁺	Uranyl ion
USFDA	US Food and Administration
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

1 Introduction

To live a healthy life, one must have access to clean drinking water. The need for clean water supplies for home and agricultural usage is rising due to the quick development of industry and population. Water shortage is becoming a major issue that practically all countries experience to some degree, but things are getting worse as industrial sectors continue to dump toxic, harmful, and persistent contaminants into water sources (Wang et al., 2021). According to UN estimates from 2006, water deficiency will affect 70% of the world's population by 2025 as a result of ongoing increases in water pollution. The main sources of water pollution, both organic and inorganic, include human activity such as overusing fertilizers and pesticides, as well as industrial effluents (Amdeha, 2023a, 2024). The large volumes of industrial effluents that are specifically thrown into water bodies contain organic pollutants such as pesticides, herbicides, antibiotics, hydrocarbons, dyes, proteins, phenols, and detergents. These pollutants diminish the dissolved oxygen levels in the water, harming aquatic systems and the environment. (Rahmani et al., 2020).

To protect clean water resources and reduce the amount of greatly polluted wastewater that is released into water bodies, current research articles spotlight environmentally friendly and reasonably priced treatment methods for the large amount of industrial wastewater that is produced before release. Numerous treatment technologies have been implemented, such as biological treatment, flotation-coagulation, electrocoagulation, and membrane processes (Ewis et al., 2021). Even though these technologies have excellent treatment efficiency, there are often issues with them, including high energy usage, capital expenses, and difficulties scaling up. Adsorption technology has gained a lot of concern because of its ease of use, low cost and energy consumption, environmental friendliness, and high treatment efficiency (Amdeha, 2021, 2023b). Adsorption is used in the polishing stage of wastewater treatment to get rid of extremely minute particles.

Two-dimensional (2D) materials and their composites have drawn a lot of attention among the different types of adsorbents because of their remarkable qualities, which include their abundance of pore structure, chemical stability, large SSA,

tunability for particular applications, ease of physical and chemical modifications, and capacity to remove a variety of contaminants (Xiong & Jivkov, 2018). Materials that are classified as 2D have atomic or molecular thicknesses; the other dimensions of these materials reach the micrometre or nanometer range. These materials' decreased dimensionality causes them to display distinctive qualities and behaviours.

Significant interest in 2D materials was aroused by the discovery of graphene in 2004, a single layer of C atoms organized in a hexagonal lattice (Geim, 2009). Many elemental or compound systems, such as graphene, graphitic carbon nitride, MOFs, TMDs, and others, can be used to create two-dimensional materials. These materials are desirable for a variety of applications due to their diverse and adjustable optical, chemical, and electrical properties (Cai et al., 2018). By adding doping, introducing flaws, or combining other materials to create heterostructures, 2D materials' characteristics can be further altered (Li et al., 2018). Chemical vapour deposition (CVD), mechanical exfoliation, and template synthesis are among the synthesis techniques for 2D materials that allow for the controlled creation of materials with the correct dimensions and properties (Kumar et al., 2022; Li et al., 2018).

Several disciplines are investigating 2D materials due to their unique features (Han et al., 2022a). They are excellent prospects for next-generation technologies and devices due to their huge surface-to-volume ratio, high carrier mobility, and variable bandgap (Zhou et al., 2021). The environmental applications of 2D-based compounds have piqued the interest of researchers worldwide, especially about their ability to adsorb contaminants in aqueous solutions. The numerous characteristics of 2D materials that make them appropriate for adsorbing a variety of different contaminants are the source of this interest.

Taking into account these facts, this chapter presents the significant studies that used 2D materials as adsorbents for the removal of different pollutants; dyes, phenols, heavy metals, radioactive materials, PFAS, and unwanted microbes. Meanwhile, the general synthesis and properties of 2D materials, and adsorption performance are discussed. The desorption studies and the suggested mechanisms are also addressed. This chapter also addresses the challenges and prospects of 2D materials as adsorbents in wastewater treatment.

2 Classification of 2D Materials

2D materials can be categorized into different groups:

Graphene Family

The graphene consists of 2D layers of sp^2 hybridized carbon atoms, arranged in a hexagonal lattice structure with a thickness of one atom. Graphene possesses unique properties e.g. a high elastic modulus, a large SSA, and high strength. Graphite is the primary precursor for graphene production and is utilized in various ways (Yadav et al., 2023). Graphene holds the distinction of being the most advanced material, finding applications in nearly every major field due to its 1-atom thick, 2D

hexagonal honeycomb structure, which grants it not only exceptional thinness but also remarkable strength. Pristine graphene synthesis is challenging due to the extreme instability of single atomic layers during the synthesis process. Graphite can be oxidized to make graphene hydrophilic and to increase the interlayer gap by using a strong oxidizing chemical during the synthesis process. This feature makes the process of exfoliating graphite into graphene layers more stable and convenient. Because graphene oxide (GO) contains oxidizing molecules, its characteristics are marginally different from those of pristine graphene. One of the GO's main benefits is the addition of terminal functional groups to its surface, which, depending on the kinds of functional groups added, might increase the material's possible applications. GO functions as an electrical insulator, nevertheless, because the sp^2 links in the layers are broken. To recover graphene oxide's original characteristics and hexagonal structure, it becomes crucial to reduce graphene oxide getting (rGO) (Garg et al., 2021).

Graphitic-Carbon Nitride (g-C₃N₄)

g-C₃N₄ has a layered planar structure like graphene, with interlayer connections made possible by H-bonding or van der Waals interactions. A triazine ring (C₃N₃) or tri-s-triazine ring (C₆N₇), is formed when the carbon and nitrogen atoms in the plane make covalent connections. Furthermore, the stacking of interlayer van der Waals contacts gives g-C₃N₄ exceptional chemical stability, resistance to acids and alkalis, and insolubility in the majority of solvents. sp^2 hybridization is seen by the C and N atoms in g-C₃N₄, resulting in a highly delocalized π -conjugated system. The typical process for creating g-C₃N₄ entails heating precursors that are high in nitrogen (e.g. urea, thiourea, melamine, cyanamide, etc.). Calcination is a type of heat treatment that has several benefits, including easy control, mild reaction conditions, and low cost. The types of precursors and reaction conditions have a close relationship with the properties of the resultant g-C₃N₄ (Xing et al., 2022).

Transition metal-based dichalcogenides (TMDs)

A transition metal (M) covalently bonds to two chalcogens (X) to generate an MX₂ structure, which is the precursor of 2D TMDs. These materials have weak van der Waals forces holding their X-M-X tri-layer covalent bonding together in their crystal structure. Tungsten disulfide, tungsten ditelluride, and molybdenum disulfide are a few TMDs examples (Zhou et al., 2018). These materials' crystal structures have a significant impact on their characteristics. By creating 2D TMDs specifically suited to certain industrial needs, desired chemical, physical, electrical, optical, and mechanical properties can be attained. Thin film synthesis techniques allow for the modification of TMD properties by changing the crystal structure's layer sequence, which can include swapping out either the metal or the chalcogenides (Yadav et al., 2023).

Mxenes

Mxenes, a unique group of 2D metal-based carbides or nitrides; $M_n^{+1}AX_n$ ($n = 1-3$); which is produced by selectively etching the raw M (transition metal), A (metal from group III or IV), and X (N or C). The layered structure of the MAX phase, in

which X fills the octahedral gaps and metal layers are stacked hexagonally, is the source of mxenes. Strong cleaning agents can be used to selectively remove the A component. Mxenes are appropriate for the elimination of different pollutants due to their high sorption selectivity (Janjhi et al., 2023).

Metal-Organic Frameworks (MOFs)

MOFs are essential for several applications. They have tunable surface area, unsaturated reactive sites, and modifiable surface characteristics. MOFs have a wide range of uses because they are unique structures created by mixing organic (ligand) and metal (inorganic) components (Peng et al., 2017). Several MOFs can be produced by altering the ligand framework. Transition metals can build 2D MOFs with desired characteristics by coordinating with various ligands.

3 2D Materials Preparation Routes

The synthesis methods for 2D nanomaterials are categorized into two routes: top-down and bottom-up approaches. The top-down route involves various techniques such as exfoliation methods (micromechanical, chemical, ultrasonic, etc.) (Demirel et al., 2018). On the other hand, the bottom-up approach includes techniques like CVD, wet chemical techniques, and template synthesis. Figure 1 illustrates different types of 2D nanomaterials preparation routes.

Top-down approach

The process of converting bulk materials into nanostructures or nanoparticles (NPs) uses a top-down methodology. Comparatively speaking, it is simpler than the bottom-up strategy since it uses bulk production techniques or reduction/separation of big materials to create the desired structure with acceptable properties. However,

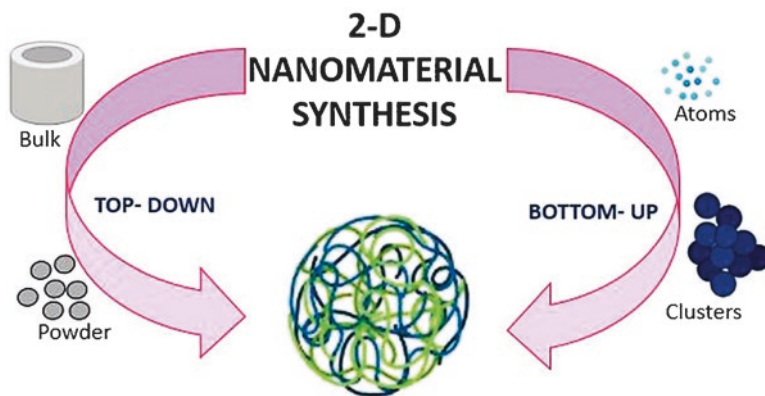


Fig. 1 Different types of 2D nanomaterials preparation routes. (Adapted with permission from (Chen et al., 2022a), © 2022 Elsevier B.V)

the primary flaw with the top-down method is the surface structure's imperfection. The top-down method produces ultrathin nanosheets through physical and chemical techniques. While the chemical top-down technique depends on processes involving heat, ion exchange, or other methods, the physical top-down method shapes van der Waals solids into single or few layers of 2D nanomaterials through the use of ultrasonic waves or mechanical force (Demirel et al., 2018).

Micromechanical exfoliation: is an easy process that preserves the crystal structure and characteristics while creating nanosheets with one or more layers. Because of its simplicity, versatility, and applicability to fundamental research, it is commonly utilized in the synthesis of 2D materials. For example, the exfoliation of 2D TMD materials was made popular when graphene and graphite were successfully separated using scotch tape. Micromechanical exfoliation is helpful for research and developing all-layered material devices, but it is not practical for large-scale production because of difficulties in managing the number and size of layers (Alam et al., 2021).

Within **ultrasonic exfoliation**, van der Waals solids are separated into single or multilayer nanosheets via lamination. Two essential elements of a successful exfoliation process are the length of the sonication and the choice of solvent. This method works better and produces more results than mechanical exfoliation does. Mass-production approachable, film-forming liquid-phase ultrasonic exfoliation offers a wide range of uses. However, it can be difficult to regulate the level of exfoliation (Liu & Li, 2020).

Bottom-up approach

Building materials atom by atom or molecule by molecule is how the bottom-up method creates nanostructures. Although this method can generate less waste, it is somewhat more costly. Bottom-up methods are widely employed in the manufacturing of industrial nanopowder. By using atomic or molecule elements that can react, expand in size, or self-assemble into more complicated frameworks, the bottom-up technique makes it possible to create nanoscale components that aid in the creation of 2D materials. There are numerous known bottom-up methods for producing 2D nanomaterials, such as chemical vapour deposition, hydrothermal synthesis, and template synthesis. According to (Ortiz & Skrabalak, 2014), the bottom-up approach is thought to be easier to use for preparing 2D nanomaterials and offers greater advantages to researchers because it uses less energy and has fewer structural flaws.

Chemical vapour deposition (CVD) is a process that produces 2D materials by reacting or disintegrating gas, liquid, or solid precursors in a carefully prepared environment. Chemically active substrates are the best choice for CVD, and the production process can be done at ambient to ultrahigh pressures. Transition metal dichalcogenide (TMD) layers with the appropriate electrical characteristics and diameters can be easily produced by the CVD process. Metals, semiconductors, and separators are among the materials that can be used to coat. Two comparable processes are used in this method: CVD growth of single and polycrystalline graphene (Alam et al., 2021).

TMDs with a variety of thicknesses, from single layers to many layers, can be prepared using **Wet chemical techniques**. Comparing the produced materials to CVD, they are much more uniform and have less deformation thickness. By introducing different chemicals throughout development, materials can be doped using wet chemical methods. Additionally, the surface of the material can be altered or smoothed by coating it with ligands. Since the TMDs are frequently employed in larger-scale manufacturing processes, wet chemical procedures might also be advantageous for them. Green chemistry and manufacturing requirements can be met by adapting solution-based processes to include ecologically acceptable precursor compounds (Miró et al., 2014). Chalcogenides are traditionally made by two wet chemical processes: hydrothermal development and solvothermal development.

Template synthesis: the key component of a template-assisted synthesis is the “template,” which can be any material with nanostructured features, whose size, shape, and charge distribution substantially affect the structure guiding properties. In the template-assisted synthesis method, the template preparation step is the first. The next step is to use the template to create the needed material and, if necessary, remove it. To create the necessary material, one can employ chemical or physical methods such as addition, removal, substitution, or isomerization reactions or surface coating. Using physical techniques like dissolving or chemical methods like calcination, the template can be eliminated once the reaction is finished. The main advantage of this process is that it allows for good control over the final product’s morphology, dimension, and structure. This approach has been used to create a variety of TMDs with different morphologies. Template-assisted synthesis can be further divided into three categories: colloidal, soft, and hard templates, depending on the kind of template that is accessible (Alam et al., 2021).

4 Properties of 2D Materials

The physicochemical properties of the used adsorbent determine how well 2D-based materials can remove various contaminants. Common physicochemical characteristics that have a significant impact on pollutants’ adsorption include SSA, porosity, hydrophilicity, toxicity, stability, and the presence of various functional groups on adsorbent surfaces (Bilal et al., 2023). The physicochemical properties of 2D materials’ components, which in turn influence their adsorption potentials, are frequently influenced by the synthesis pathways used to create them. On the surface of 2D adsorbents, several functional groups; e.g. –OH, –O, and –F; frequently form during etching processes (Zhang et al., 2018).

The adsorption of pollutants often increases in tandem with an adsorbent’s expanding SSA because adsorption is mostly a surface phenomenon (Bilal et al., 2022). Gaining more surface area may result in many more pores (more active locations) that target pollutant molecules and may be able to adsorb. High SSAs typically result in greater adsorption capacity because they offer more active sites for the adsorption of contaminants.

Surface functional groups: A significant role in removing pollutants from the aqueous environment can also be played by the readily accessible surface functional groups of 2D adsorbents. The reason for this is that the (–) or (+) charged functional groups of the adsorbents have strong binding interactions with the oppositely charged pollutant molecules. These interactions frequently lead to increased pollutant uptake by the adsorbents that are used. For instance, because of the electrostatic attraction between the opposing species, the existence of (+) charged functional groups on the surfaces of the 2D adsorbents would facilitate the adsorption of the anionic dye. Given that they contribute to the different chemical and physical features of the 2D adsorbents, the existence of diverse surface functional groups is crucial for the application of 2D adsorbents (Sajid, 2021).

Another factor that significantly influenced an adsorbent's capacity for adsorption was its **surface wettability**. The targeted pollutant's selective adsorption can be significantly influenced by the wettability of the used 2D adsorbents (Bilal et al., 2023).

5 2D Materials as Adsorbents for Wastewater Pollutants

To sustain a healthy lifestyle, clean drinking water must be readily available (Baig et al., 2019). Continuous wastewater discharge from several sources needs to be treated to enhance water quality, lessen diseases and health issues, and provide an ecosystem that is conducive to aquatic life.

5.1 Adsorption of Organic Pollutants

Adsorption of Dyes

Organic pollutants, including dyes, are used for a variety of purposes and can be fatal if disposed of improperly in untreated natural water. Many sectors, such as textile, paper industries, printing, food processing, leather, and dye manufacturing, utilize dyes often. However, throughout the dyeing process, more than 10–15% of the dye output is lost, and as a result, a significant amount of the dye ends up in wastewater. Because of their poisonous and carcinogenic qualities, they are regarded as a significant source of water contamination (Amdeha & Salem, 2022; Deriase et al., 2021; El-Salamony et al., 2023).

According to (Mantasha et al., 2020), 2D MOFs, $[M(ox)(bpy)]_n$ [H_2ox = oxalic acid, bpy = 4,4'-bipyridine and M = Cu (1) or Co (2)], were synthesised via solvothermal (Fig. 2). MB and MO, two organic dyes that are commonly regarded as water contaminants, are adsorbed onto the two MOFs. Remarkably, the cationic dye MB exhibited selectivity towards the molecular frameworks. The framework can be recycled up to five times and stays stable following the adsorption of dye. The frameworks remove the maximum amount of MB (96–98%) at equilibrium, with a

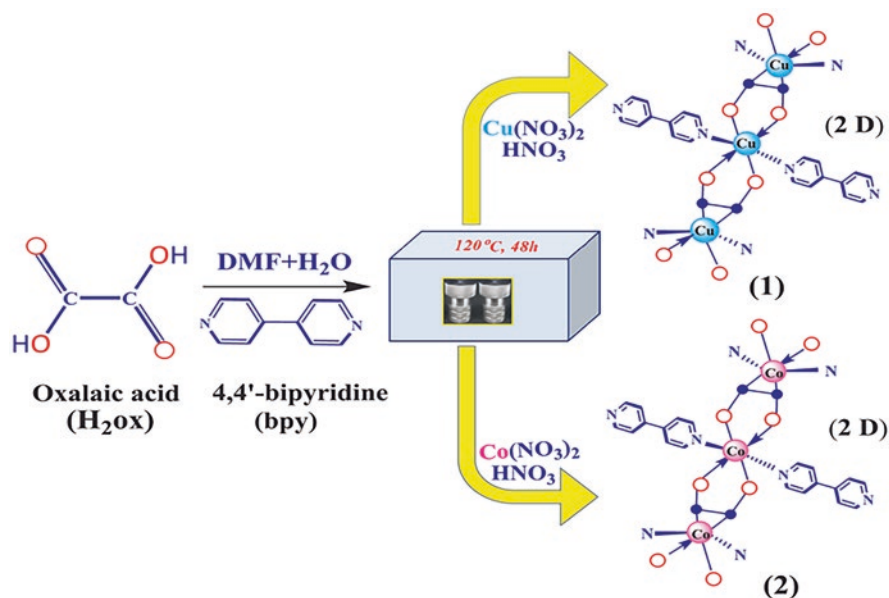


Fig. 2 Synthetic route of 1 and 2. (Adapted with permission from (Mantasha et al., 2020), © 2020 Elsevier B.V)

pH of neutral and $T = 25^\circ\text{C}$. According to the kinetic studies, the adsorption will likely proceed through a pseudo-second-order process.

$\text{Ti}_3\text{C}_2\text{T}_x$ MXene was employed as an adsorbent by (Kadhom et al., 2022) to remove Malachite Green (MG) dye, taking into account the dye's chromatic and leuco forms. The Freundlich model got the highest R^2 , 0.97, and was the best-fitting isotherm model. The model with the pseudo-second order has the highest R^2 of 0.99. Results showed that removal effectiveness rises with increasing adsorbent dose; at 0.09 g in a 50 ml solution, removal efficiency reached 94.1%. It is noteworthy to observe that the removal increases with changes in pH, with the minimum efficiency seen at $\text{pH} = 6$. This was explained by the dye's leuco nature, which causes it to become colourless and more difficult to detect as pH rises. The results indicate that removal is higher at low pH values and decreases as pH increases, but colour loss makes these differences intangible.

Through the use of amphiphilic CNDs, (Yin et al., 2022) effectively exfoliated hydrophobic bulk MoS_2 into 2D nanosheets, Fig. 3. Higher than that of the literature, the optimal dose of the obtained 2D- MoS_2 is 0.41 mg/ml. Two dimensions of 2D- MoS_2 are $142.6 (\pm 2.3)$ nm in length and 4 in terms of layers, on average. CNDs can be instantaneously adsorbed on the surface of 2D- MoS_2 to produce 2D- MoS_2 /CNDs. Because of CNDs, the amount of 2D- MoS_2 remains 90% of the initial concentration even after standing for 1000 hours. Because there are many adsorption sites and high dispersion, the 2D- MoS_2 /CNDs composite has a great Q (1137 mg/g) and an incredibly quick adsorption rate (one minute) for the removal of MB.

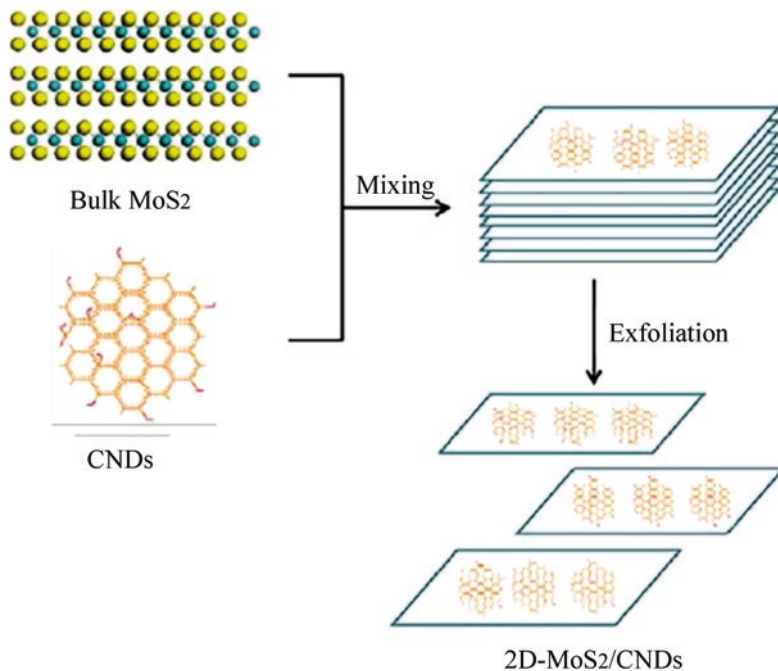


Fig. 3 CNDs as dispersing agents for exfoliating and dispersing MoS₂. (Adapted with permission from (Yin et al., 2022), © 2022 Elsevier B.V)

Adsorption of Phenols

Organic substances combined with benzene rings and OH-groups to form additional aromatic compounds are known as phenolic pollutants. Starting with phenol, several polymers can be synthesized. Phenolic pollutants have serious detrimental impacts on human health and are regarded as priority pollutants. High levels of phenols are found in the effluents produced by various industries, including fertilizer, plastic, coking, pharmaceutical, and refinery industries, as well as home trash (Rout & Jena, 2022c). In bottled drinking waters, the USFDA has set a phenol concentration of 0.001 mg/L and in groundwater, 0.01 mg/L. For this reason, before water is released into the environment, the content of phenolic contaminants in it should be decreased.

To remove phenol, rGO was used as a sorbent; at 25 °C and neutral pH (Rout & Jena, 2022a), its sorption capacity was 602 mg/g. It was shown that the reduction of GO improved the adsorption performance. The regeneration studies demonstrate that following five cycles, the phenol removal stayed at 78.3%. To aid in the sorption of phenolic chemicals e.g. 2-CP, phenol, and 2,4-DCP, (Rout & Jena, 2022b) have prepared an adsorbent composed of rGO-modified epichlorohydrin cross-linked beta-cyclodextrin (rGO-βCD-ECH). According to the authors, this composite's maximum adsorption was 674, 659, and 703 mg/g, for these phenols,

respectively. By forming a host-guest inclusion complex with the phenolic compounds, the modification of β CD may improve its adsorption capacity.

Adsorption of PFAS as emerging pollutants

A group of highly fluorinated aliphatic compounds known as Perfluoroalkyl and poly-fluoroalkyl substances (PFAS) are those in which fluorine atoms partially (poly-fluoroalkyl acids) or totally (perfluoroalkyl acids) replace H-atoms affixed to carbon chains. Fluorinated carbon chains are not the only functional groups found in PFAS—terminal functional groups can be carboxylic, phosphonic, sulfonic, sulfonamide, phosphinic, or ether sulfonic. According to (Phong Vo et al., 2020), PFAS are best suited for use in many applications e.g. fire fighting foams, waterproof fabrics, stain repellents, food packaging, cleaning products, non-stick cookware, electrical wire coverings, and metal plating because of their special combination of chemical and thermal stability and hydrophilic-lipophilic characterization. 4730 registered PFAS have been synthesized over the previous 70 years as a result of these numerous applications (Pauletto & Bandosz, 2022). Research has been done on numerous human exposure pathways to PFAS, Fig. 4.

Depending on how long their carbon chains are, PFAS are divided into subclasses. Perfluoroalkyl sulfonic acids (PFSA; $C \geq 6$) and perfluoroalkyl carboxylic acids (PFCA; $C \geq 8$) are referred to here as “long-chain” acids. According to (Pauletto & Bandosz, 2022), PFCA; $C \leq 7$ and PFSA; $C \leq 5$ are referred to as “short-chain” compounds. Emerging persistent organic pollutants are those that contain perfluoroalkyl acids (PFAA).



Fig. 4 Sources of PFAS. (Adapted with permission from (Yadav et al., 2022), © 2022 Elsevier B.V)

The octanol-water partition coefficients (K_{ow}) show that PFAS becomes more hydrophobic as the C–F chain length increases. The functional groups that are linked to the hydrophilic C–F chains, despite their hydrophobic nature, make PFAS soluble in water (Gagliano et al., 2020). PFAS are found in the environment in their (–) charged as shown by the low values of pK_a . According to (Saeidi et al., 2021) these physicochemical characteristics demonstrate the bioaccumulative, persistent, and spreadable nature of PFAS under many circumstances. According to (Wu et al., 2021) exposure to PFAS can impact an individual's immune system, making them more vulnerable to cause COVID-19. In many countries, the amount of PFAS in water is higher than what is advised. Thus, to protect the health of everyone on the planet, effective methods for removing PFAS from polluted water must be implemented.

According to (Yang et al., 2020), perfluorooctanoic acid (PFOA) was found to adsorb onto MIL-100-Fe and MIL-101-Fe. When $C_o = 1000$ mg/L, Q was 370 mg/g for MIL-101-Fe and 349 mg/g for MIL-100-Fe, according to their experimental data. The ligands were 1,3,5-benzene tricarboxylic acid and 1,4-benzene dicarboxylic acid for MIL-100-Fe and MIL-101-Fe, respectively, and the pore structure was identified as the cause of this difference. Only MIL-101-Fe had triangular pores, which may have led to the increased PFOA adsorption. The authors proposed several mechanisms for the adsorption behaviour, in which the Lewis acid-base complexation was proposed as the primary adsorption process.

As described by (Barpaga et al., 2019), Per fluoro octane sulfonic acid (PFOS) adsorption on MIL-101-Cr and MIL-101-Fe was compared. The micelles most likely formed under these circumstances, as the C_o of PFOS was 4141 mg/L. The exposed terminal sulfonic groups were therefore more likely to interact with the adsorbent surfaces than the fluorinated carbon chain of PFOS. MIL-101-Cr was able to adsorb PFOS to a larger extent and double as rapidly as MIL-101-Fe, according to the results of fluorine NMR.

5.2 Adsorption of Inorganic Pollutants

Adsorption of Heavy Metals

Pesticides, mining, electroplating, painting, and other industrial operations release a significant amount of heavy metal ions (HMI) (Hg^{2+} , Cd^{2+} , Pb^{2+} , Cr^{3+} , Cr^{6+} , etc.) into the aquatic ecosystem. The removal of more than one hundred HMI from wastewater requires the development of effective and eco-friendly technology due to the potential health risks posed by dissolved HMI, which can arise from their toxicity, persistence, and bioaccumulation. According to (Zhang et al., 2023), adsorption presents a lot of promise because of its low cost and simplicity of use.

The $Ti_3C_2T_x$ MXene/chitosan/lignosulfonate adsorbent (MCL) was created by (Othman et al., 2023) using chitosan/lignosulfonate nanospheres as a simple way to decorate $Ti_3C_2T_x$ MXene sheets. This renewable and biodegradable addition can enhance the MXenes' aqueous stability and biocompatibility. To give MXene sheets

a range of surface functions, high SSA, and antioxidant properties, chitosan/ligno-sulfonate nanospheres were stabilized on their surface. In multi-metal systems, competitive adsorption demonstrated that MCL had a preferential adsorption affinity toward different HMIs; in neutral pH settings, the MCL adsorption removal followed a sequence of $Pb^{2+} > Cr^{6+} \approx Cu^{2+} > Ni^{2+} \approx Co^{2+}$. On the ions Cu^{2+} and Cr^{6+} , a moderate reduction was noted. It is proposed that surface complexation, ion exchange, and electrostatic interaction work synergistically to form the adsorption mechanism.

Green synthesis and in-situ polymerization techniques were utilized by (Raza et al., 2023) to build a unique form of conducting polymer based on 2D materials. Glycidyl methacrylate (GMA) was used to functionalize the 2D molybdenum disulfide (MoS_2), resulting in the formation of $MoS_2@PGMA$. The $MoS_2@PGMA$ is then mixed with polyaniline (PANI) by the grafting method, as shown in, Fig. 5, to create conducting polymer grafted thin film nanosheets with a thickness of micrometer size. The maximum Q for Cu^{2+} and Cd^{2+} was 307 mg/g and 214 mg/g, respectively, producing amazing results. The prepared nanosheets can be successfully recycled and recovered for five cycles. It is anticipated that the established process for preparing $MoS_2@PGMA/PANI$ and manufacturing the 2D materials would work for a variety of further applications.

2D iron oxide-hydroxide ($FeOOH$) nanoparticles, which are inexpensive and environmentally benign composites are considered promising materials for HMIs removal. Due to the naturally non-layered structure, it is currently difficult to create 2D $FeOOH$ adsorbents with high Q for Cr (VI) removal. In this regard, (Wu et al.,

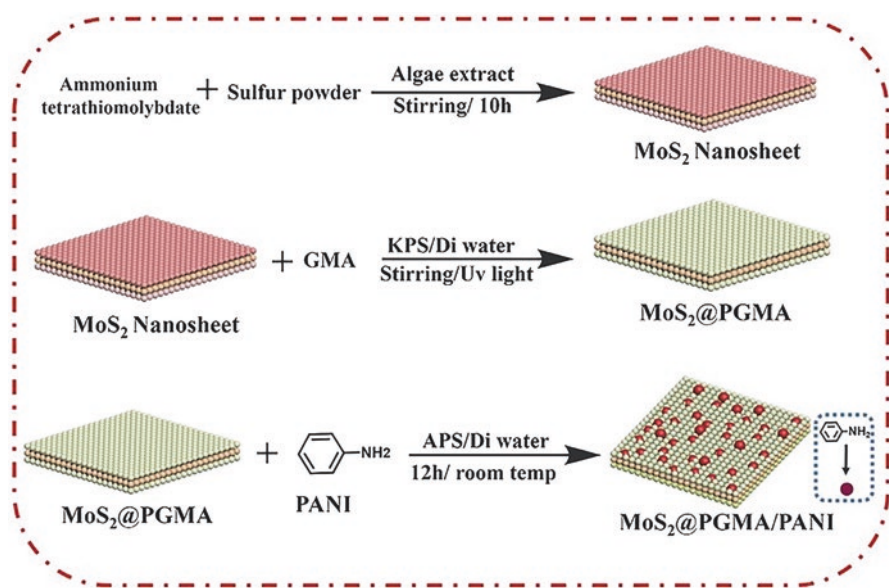


Fig. 5 Preparation of MoS_2 , $MoS_2@PGMA$, and $MoS_2@PGMA/PANI$. (Adapted with permission from (Raza et al., 2023), © 2023 Elsevier B.V)

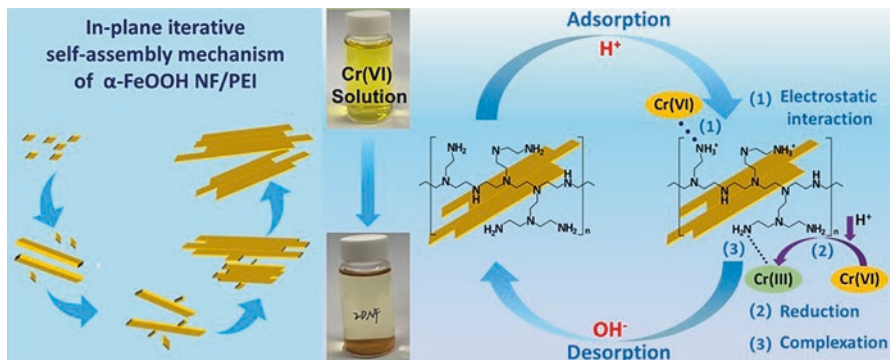


Fig. 6 Self-assembly mechanism of 2D α -FeOOH NF/PEI and the adsorption and desorption of Cr (VI) ions. (Adapted with permission from (Wu et al., 2023), © 2023 Elsevier B.V)

2023) prepared a unique 2D single-layer nano-raft-like α -FeOOH (α -FeOOH NF) functionalized with polyethyleneimine (PEI) via a simple one-pot hydrothermal method, featuring ultrathin nanowires that are oriented parallel to one another, Fig. 6. Anisotropic development of α -FeOOH served as intermediates and iterative seeds in the formation of the 2D NF nanostructure, which was discovered to be the result of an in-plane iterative self-assembly mechanism. The 2D α -FeOOH NF has a high SSA and porous structure that makes it highly effective at capturing Cr(VI) ions in water. Because of its special structure and PEI modification, it demonstrated high Q for the Cr(VI) removal, a quick adsorption kinetic rate, and good reusability. The suggested removal mechanism included both adsorption and reduction processes. The fifth cycle showed a removal effectiveness of 83.9% whereas the Q was 67 mg/g.

Adsorption of Radioactive pollutants

Nuclear power is seen as a viable substitute for addressing the growing demand for energy due to the scarcity of conventional fossil resources (Chen et al., 2022b). However, throughout the development of nuclear energy, a huge number of radionuclides with long half-lives and great mobility are released into the water, including uranium (^{235}U , ^{238}U), cesium (^{137}Cs), thorium (^{232}Th), and strontium (^{90}Sr). The emission of these radionuclides causes high levels of heat, radiation, toxicity, and corrosiveness in aquatic environments. Because of their long-term radiological and chemical toxicity, these radionuclides pose serious dangers and long-term threats to the health of humans and the environment, both above and below ground. This is true even at low concentrations.

Radiation exposure in aquatic environments can result in various malignancies of different organs, neurological problems, and birth defects. There are rumors that these regrettable, long-term effects became evident following the Fukushima and Chernobyl disasters. Therefore, to remove radionuclides from the environment, it is always required to develop effective, environmentally friendly, and radiation-resistant adsorbents (Nezami et al., 2023). Uranium has always been the primary

component of nuclear fuel energy. The extended half-life of uranium (4.45×10^9 years) makes it a non-essential radioactive element that poses a risk to both people and the environment. The U^{6+} is quite adaptable. Scientists have developed adsorbent materials to remove this pollutant because it quickly adsorbs in pure water, generating the far more stable UO_2^{2+} (Yu et al., 2019).

The most efficient adsorbent for UO_2^{2+} adsorption is $Ti_3C_2(OH)_2$, with $Q = 595$ mg/g. It was shown that UO_2^{2+} bound to deprotonated oxygen adsorptive sites were favoured over protonated molecules that may be accessed on surface hydroxylated sites (Zhang et al., 2020). A straightforward technique for creating and preserving pure and embedded MXene in under-hydrated conditions was presented by (Wang et al., 2017b). This method increases the gap between the layer of $Ti_3C_2T_x$ MXene. Using a hydrated intercalation strategy, the researchers demonstrated an unexpectedly substantial enhancement in $Ti_3C_2T_x$'s adsorption capacity for radioactive isotope rejection. This procedure, known as "radioactive imprisoning," was based on rapid low-temperature post-adsorption calcination.

By carefully controlling the interlayer spacing between the layers of MXene, they were able to confirm that U^{6+} could be captured within the multilayer $Ti_3C_2T_x$. The soaked $Ti_3C_2T_x$ NMs with DMSO significantly improved their adsorption behaviour for U^{6+} , and $Q = 214$ mg/g, as compared to dry $Ti_3C_2T_x$. (Sun et al., 2018) experimented on $Ti_3C_2T_x$ /g- C_3N_4 to confirm the effect of the $-OH$ surface functional group on the MXene-based adsorbent's ability to adsorb. During their examination, they confirmed that MXene with a $-OH$ surface group has strong bonding energy between 3.3 and 4.5 eV. This suggests that MXene with this type of surface group could be used as a good adsorbents to reject radioactive materials from nuclear effluent.

Even at low concentrations, the major nuclear by-product Europium poses a health risk to the general public because it is harsh and must be released into the environment by nuclear reactors. (Zhang et al., 2019) prepared hierarchical titanite nanostructures (HTNs) using an in situ oxidation conversion process, starting with $Ti_3C_2T_x$ MXene precursor. The generated HTNs appear to be exceedingly robust and have large sorption capacities for Eu^{3+} because of their extensively interchangeable guest cations and well-maintained multilayer architecture. Effective adsorption of $Eu^{3+} > 200$ mg/g was demonstrated by the produced HTNs. Eu^{3+} was desorption by an ion-exchange mechanism, where H^+ , Na^+ , and K^+ were exchanged by solid H -bonds and electrostatic attraction. Verification of Eu^{3+} displacement for Na^+ or K^+ ions in HTN nanolayers has been confirmed by XPS and XRD. When it comes to environmental remediation, these HTNs are appealing substitutes for removing and cleansing actinides and trivalent lanthanides from aqueous solutions. During the experiment, several parameters are provided that impact how well HTNs work.

Thorium is still regarded as a major resource and the most promising substitute energy source for ^{233}U due to its fertile nature. From the Ti_2AlC precursor, (Li et al., 2019) synthesized $Ti_3C_2T_x$ -hydrated and $Ti_3C_2T_x$ -dry. The studies' ultimate conclusion is that $Ti_3C_2T_x$ -hydrated MXene has $Q = 213$ mg/g, which is significantly higher than the adsorption capacities of many other popular inorganic adsorbents. Furthermore, the $Ti_3C_2T_x$ -hydrated material exhibits exceptional adsorption

selectivity against Th^{4+} when the right metal ions are present. According to the present research, Th^{4+} pre-concentration and extraction could benefit from the use of $\text{Ti}_3\text{C}_2\text{T}_x$ -hydrated.

6 Adsorption Mechanism

It is necessary to evaluate mechanism studies to have a thorough understanding of the adsorption of potentially hazardous contaminants. An understanding of the adsorption mechanism requires the application of some spectroscopic techniques, adsorption isotherms and kinetics, and theoretical computations like DFT. According to (Wu et al., 2019), the surface functional groups and numerous reaction sites of new nanomaterials might help with the effective removal of various contaminants.

The type of the adsorbate and the adsorbent surface properties are related to the adsorption mechanism. When additional materials are added to an adsorbent, the surface characteristics and interaction are altered, which ultimately impacts the adsorption mechanism. The most often reported adsorption mechanisms for 2D adsorbents against various water pollutants include ion exchange, H-bonding, $n-\pi$ interaction, surface complexation, electrostatic interaction, van der Waals, hydrophobic interaction, and chemical adsorption (e.g., covalent bond). The structure, surface characteristics, and functional groups of the 2D adsorbents, as well as the chemical characteristics of the pollutant, determine the dominant adsorption mode. Additionally, as the adsorbent surface properties can be changed by the adsorption circumstances, such as pH and ionic strength, these factors have an impact on the adsorption mechanism (Ewis et al., 2022).

Ionic bonds are formed through **electrostatic interaction**, which consists of both electrostatic attraction and repulsion. It developed between negative anions and positive cations as a result of electron loss and gain in atoms. Analyzing the impact of solution pH on the adsorbent's ability for adsorption is important. This is so because changes in the pH of the solution can affect the charges on the surface of the adsorbent, which in turn affects the electrostatic interaction (Ewis et al., 2022).

As GO, for example, provides a benzene ring, the **$n-\pi$ and $\pi-\pi$ interactions** were in charge of the adsorption process. Unsaturated bonds on both the aromatic rings of the adsorbent and the adsorbate interact weakly through the $\pi-\pi$ interaction (Chua et al., 2021).

Ion exchange is the process by which ions of the same charge are exchanged between the adsorbent and the adsorbate. To keep the solution electrically neutral, it happens when the adsorbent adsorbs ions from the solution and releases equivalent ions back into the solution. A form of dipole-dipole attraction known as **hydrogen bonding** occurs when an electronegative atom, such as N, O, or F, bonds to a H atom. **Surface complexation**: may be a factor in how minerals and clay interact with organic contaminants. According to (Yang et al., 2019), surface complexation is the result of the adsorbent and adsorbate interacting electrostatically while the

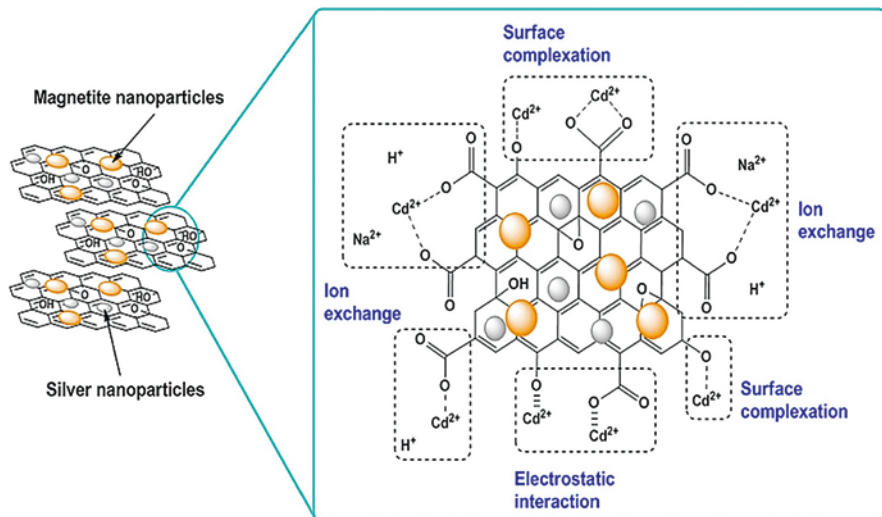


Fig. 7 Suggested adsorption mechanisms for Cd^{2+} on the rGO/magnetite/silver NH sample. (Adapted with permission from (Park et al., 2019), © 2019 Elsevier B.V)

adsorbate ions maintain their hydration sphere. The primary forces behind adsorption were surface complexation, ion exchange, and electrostatic attraction Fig. 7.

7 Desorption and Regeneration Studies

An essential step in managing the cost of the adsorbent, environmental risks, and the hazardous sludge disposal issue is ensuring that pollutants can be recovered from the loaded 2D adsorbents and that they can be reused. A variety of eluents, including HCl, NH_4OH , HNO_3 , H_2SO_4 , NaOH, Na_2CO_3 , KOH, DI-water, and Na_2EDTA , have been applied in the literature to aid in the desorption of pollutants that have been adsorbed by 2D adsorbents (Bilal & Ihsanullah, 2022). When choosing an appropriate adsorbent, one of the most crucial factors is its renewability. Adsorbents with high contaminant adsorption on their surface at equilibrium, more than the quantity of contaminant left in the water solution, typically exhibit sluggish or ineffective desorption/regeneration, which restricts their use in wastewater treatment (Vakili et al., 2019).

If adsorbents are not recycled, the adsorption process becomes more expensive and there is a chance that the contaminant will be discharged into the environment during disposal or storage of the worn adsorbent. By recovering pollutants from the used adsorbent, the cost of the adsorption process can be decreased because the regenerated adsorbent can be used continuously. Consequently, there are significant

financial and environmental benefits to recycling the wasted adsorbent through the implementation of a suitable regeneration technique.

Chemical regeneration involves applying a solvent at a specific pH and temperature, which breaks the adsorption equilibrium between the solvent, adsorbent, and adsorbate. Chemical solvents can be either organic, like methanol or inorganic, like HCl and NaOH. For organic pollutants with a low boiling point and high concentration, chemical regeneration is an appropriate regeneration technique. Furthermore, the primary factor influencing the effectiveness of the regeneration process is the adsorbate's solubility in the solvent. Solvent regeneration poses a primary concern as it has the potential to modify the structure of the adsorbent, hence impacting its efficiency in subsequent adsorption cycles (Momina et al., 2020). One crucial thing to keep in mind is that the chemical regeneration process is hampered and/or ineffective in regenerating the composite when the pollutant is firmly adsorbed on the surface of the composite and within its micropores. This is an important problem for composites that get highly bound to organic pollutants and have a micropore-like structure. Consequently, it is advisable to take into account alternate regeneration methods. As part of the regeneration process, the concentration of the solvent is a crucial consideration. An increased concentration of solvent improves regeneration. Regenerating adsorbents is not aided by exceptionally high solvent concentrations, nevertheless. Consequently, appropriate research should be done on the influence of solvent concentration. For example, research has shown that MB desorption is improved when the concentration of HCl is increased from 0.001 M to 0.1 M. In addition, temperature has a significant role in the regeneration of 2D composites. By changing the adsorbate's molecular activity and decreasing the adsorbate-adsorbent interaction, temperature can accelerate the rate of desorption (Mansour et al., 2018). Furthermore, heating increases the organic contaminants' solubility in the solvent. Another crucial element is the timing of desorption. Since more interaction between the adsorbate and the solvent is possible, longer desorption times generally result in faster desorption rates. The predicted duration for 2D composites ranged from 3 to 24 hours. Nonetheless, the majority of these investigations purposefully prolonged the desorption period to guarantee that the system attains the desorption equilibrium. Therefore, to achieve the highest desorption efficiency during the regeneration process, it is necessary to analyze temperature, solvent concentration, the kind of interaction between the adsorbate and the adsorbent, and the contact time.

The **ultrasonication** procedure comprised soaking the used adsorbent for an hour in 10 millilitres of pure ethanol and then ultrasonicing it for 30 minutes.

During **thermal regeneration**, the adsorbent was subjected to a high temperature, which could break the connection that holds the adsorbate and adsorbent together. The adsorbent's weight could be decreased and its form changed by the thermal heat produced. Additionally, because thermal regeneration involves extremely high temperatures, adsorbents with limited mechanical strength and low thermal stability cannot be thermally regenerated.

8 Antimicrobial Activity of 2D Materials

Waterborne diseases result in the deaths of about five million people annually (Fahimirad et al., 2021). This dramatic impact makes finding antimicrobial agents a hot topic for research. Antimicrobials are inhibitory substances for the growth of microorganisms (Di Martino, 2022). The development of new antimicrobial substances is crucial for overcoming such diseases.

2D materials as novel, effective antimicrobial substances may provide new solutions to the microbial infection problem. Such 2D materials have some advantages for antimicrobial applications compared to other structures. The ultra-large surface area of 2D materials makes them suitable carriers for antimicrobial drugs. 2D materials interact with microbial cells via physical and chemical modes, which dramatically reduces the ability of the microorganisms to develop antimicrobial resistance. The photothermal and photocatalytic properties of some 2D materials enable them to eradicate microorganisms regardless of drug resistance (Sun & Wu, 2018).

Graphene, as a 2D carbon material, has gained attention for its antimicrobial properties. Graphene materials are easy to prepare and are renewable. They have unique catalytic properties, a large specific surface area and mechanical strength (Kumar et al., 2019). The antibacterial activity of graphene-based materials towards *Escherichia coli* (*E. coli*), including graphite and its oxide, graphene oxide, and reduced graphene oxide, was explored (Liu et al., 2011). The density of the graphene edges was the main parameter that contributed to the antibacterial property of the graphene films (Pham et al., 2015). Graphene nanosheets form pores in the bacterial cell wall, causing a subsequent osmotic imbalance and cell death (Pham et al., 2015).

The antibacterial properties of MXenes have been explored in various studies, highlighting their effectiveness against different types of bacteria and their applications in biomedical engineering, separation membranes, and wastewater treatment. MXenes are a new class of 2D antibacterial nanomaterials introduced by (Rasool et al., 2016). $Ti_3C_2T_x$ showed higher antimicrobial activity than graphene oxide toward *E. coli* and *Bacillus subtilis*. The direct contact between $Ti_3C_2T_x$ and bacterial cells can disrupt cellular membranes, leading to cell damage and death (Rasool et al., 2016). AgNPs-decorated $Ti_3C_2T_x$ membranes have anti-biofouling ability (Pandey et al., 2018). The bactericidal mechanism of MXenes is still largely unexplored.

MOFs have gained attention in antibacterial applications due to their unique properties and potential for controlled release of antibacterial agents. MOF-based bimetallic nanocomposites have also shown superior antibacterial activities against *E. coli* and *B. subtilis* compared to chemical antibiotics (Kim et al., 2023). The antibacterial activity of MOFs can release active biocidal agents in a sustained manner, contributing to their excellent antibacterial activity (Chattopadhyay et al., 2021). MOFs can be designed to contain organic antibacterial ligands that can be released in a controlled manner, leading to antibacterial activity (Li et al., 2021). The self-degrading MOFs with organic antibacterial ligands have also demonstrated

antibacterial activities through the controlled release of these ligands (Liu et al., 2019). MOFs can involve metal ions, such as copper ions, which have antibacterial behaviour (Fu et al., 2020). The slow release of copper ions from MOFs contributes to their improved antibacterial activity against bacteria like *Staphylococcus aureus* and *E. coli* (Fu et al., 2020). MOFs can disrupt the integrity of bacterial cell membranes, leading to drug internalisation and antibacterial effects. MOFs perform as catalytically active sites, mimicking enzymes and acting as photosensitisers, all contributing to their antibacterial activity (Han et al., 2022b). MOFs can act as photocatalysts, generating reactive oxygen species (ROS) upon light irradiation, which exhibit antimicrobial effects (Li et al., 2021). The broad-spectrum antibacterial action of MOFs against various oral infections is attributable to the synergistic effects of released ions from MOFs and ROS (Li et al., 2021).

The antimicrobial activity of $g\text{-C}_3\text{N}_4$ depends on its photocatalytic properties (Sun & Wu, 2018). $g\text{-C}_3\text{N}_4$ has a high surface area, which allows for increased contact between the material and microorganisms, enhancing its antimicrobial efficacy (Mallikarjuna et al., 2021). $g\text{-C}_3\text{N}_4$ has been found to generate ROS under light irradiation, such as hydroxyl radicals ($\bullet\text{OH}$), which have strong antimicrobial properties (Niu et al., 2012). These ROS can damage the microbial cell membranes and DNA, leading to their inactivation (Mallikarjuna et al., 2021).

Doping can enhance the antimicrobial activity of $g\text{-C}_3\text{N}_4$. Loading silver (Ag) nanoparticles onto $g\text{-C}_3\text{N}_4$ improved its antimicrobial activity against multidrug-resistant pathogens (Mallikarjuna et al., 2021). Similarly, modifying $g\text{-C}_3\text{N}_4$ with copper (Cu) ions enhances its visible light photocatalytic properties, which can contribute to its antimicrobial activity (Li et al., 2020). In addition, $g\text{-C}_3\text{N}_4$ nanosheets have peroxidase-like activity, which can be applied for disinfection (Tian et al., 2013). Incorporating H_2O_2 with $g\text{-C}_3\text{N}_4\text{@AuNPs}$ inhibits biofilm formation (Wang et al., 2017a).

9 Challenges and Future Perspectives

There have been encouraging possibilities for treating wastewater using 2D materials as adsorbents. Even still, there are several significant obstacles connected to 2D adsorbents that need more future perspectives:

- Certain synthetic 2D materials lack functional groups and are therefore only suitable as single-layer adsorbents, which limits their ability to be enhanced and improved for better adsorption capacity.
- In the laboratory, 2D adsorbents are prepared, but before they can be sold or commercialized, they are encapsulated, which may cause them to lose some of their surface characteristics and large SSA.
- A theoretical calculation is necessary to determine the relationship between pollutants and 2D adsorbents and how to enhance the sorption performance.