

# Emerging Two-Dimensional Materials in PFAS Remediation: A Comprehensive Review of Adsorption Mechanisms and Efficiency

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## Research Article

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# Emerging Two-Dimensional Materials in PFAS Remediation: A Comprehensive Review of Adsorption Mechanisms and Efficiency

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## Abstract

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are extensively applied in both industrial and consumer products. To overcome the drawbacks of traditional treatment techniques, researchers are increasingly exploring two-dimensional (2D) materials as innovative solutions for PFAS remediation. Due to their distinctive properties, 2D materials exhibit significant potential for environmental remediation applications. This review examines a range of 2D materials, including graphene, MXenes, 2D metal-organic frameworks (MOFs), covalent organic frameworks (COFs), layered double hydroxides (LDHs), phosphorene, and hexagonal boron

nitride (h-BN). It highlights their efficacy in adsorbing PFAS from water. By exploring the results of performance from available literature, it can be stated that graphene has been among the best-performing materials for a number of reasons. These reasons include its extensive surface area and the ability to alter its surface chemistry to capture PFAS via adsorption. Due to their structural and electrochemical stability, as well as the capacity to remove PFAS from waters of different matrices/conditions, MXenes (although with a limited number of reports) were the second-best-performing material. In addition, among the 2D MOFs and COFs, the ability to adsorb PFAS efficiently was attributed to their engineered porous frameworks. LDHs also have an effective surface for capturing PFAS in the waters because their silicate layers are positively charged, and PFAS are negatively charged. h-BN, which possesses a graphene-like layered architecture, provides remarkable chemical and thermal stability. Phosphorene, although less studied, exhibits a highly reactive surface owing to its high electron density, suggesting significant potential for adsorption applications.

**Keywords:** adsorption; PFAS; graphene; MXenes; 2D MOFs; COFs; LDHs

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## 1. Introduction

Approximately two-thirds of the Earth's surface is covered by water, with the vast majority of it (97%) found in salty oceans (Abd-Elaty et al. 2022). Freshwater comprises just approximately 3% of the Earth's total surface water, predominantly trapped in glaciers and polar ice. The globe is confronting a worsening water crisis, driven by increasing populations, rapid urbanization, environmental contamination, and climate change. The United Nations forecasts that by 2050, more than half of the global population will reside in regions experiencing water scarcity, exacerbating the strain on the planet's finite freshwater resources (Obiuto-Nwankwo et al. 2024). Currently, over 1.1 billion individuals around the world are deprived of clean drinking water as a result of insufficient sanitation systems. Consequently, numerous waterborne illnesses emerge, leading to more than 2.2 million deaths annually (Mazhar et al. 2025). The rising apprehension over chemical contamination underscores the necessity of safeguarding freshwater, a limited yet essential resource for sustaining human existence and ecosystems. Agriculture globally utilizes around 70% of all freshwater resources through irrigation and livestock cultivation. In contrast, industrial applications account for approximately 19%, while residential or municipal usage accounts for the left (Biswas et al. 2025).

Per and Polyfluoroalkyl Substances (PFAS) are human-made chemicals known to be harmful to ecosystems and human well-being. Over the past several decades, they have been incorporated into numerous products such as fire-extinguishing foams, aviation hydraulic oils, water-repellent fabrics, food wrappers, and cookware with non-stick coatings (Gagliano et al. 2020). PFAS environmental pollution is typically associated with industrial emissions, the use of firefighting foams, and the utilization of common consumer products (Hu et al. 2016). Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA) are the most prevalent contaminants identified in these substances. They have been found in many water sources, such as rain, rivers, drinking water, and industrial water (Liu et al. 2017); Figure 1(a) shows the chemical structure of the PFOS and PFOA compounds. Owing to their durability, PFAS can readily disseminate through water, air, and soil, and are exceedingly challenging to degrade. Environmental authorities encounter significant challenges in reliably identifying PFAS and evaluating its long-term environmental and health effects (Adams 2018). Figure 1(b) shows the water pollution cycle with PFAS.

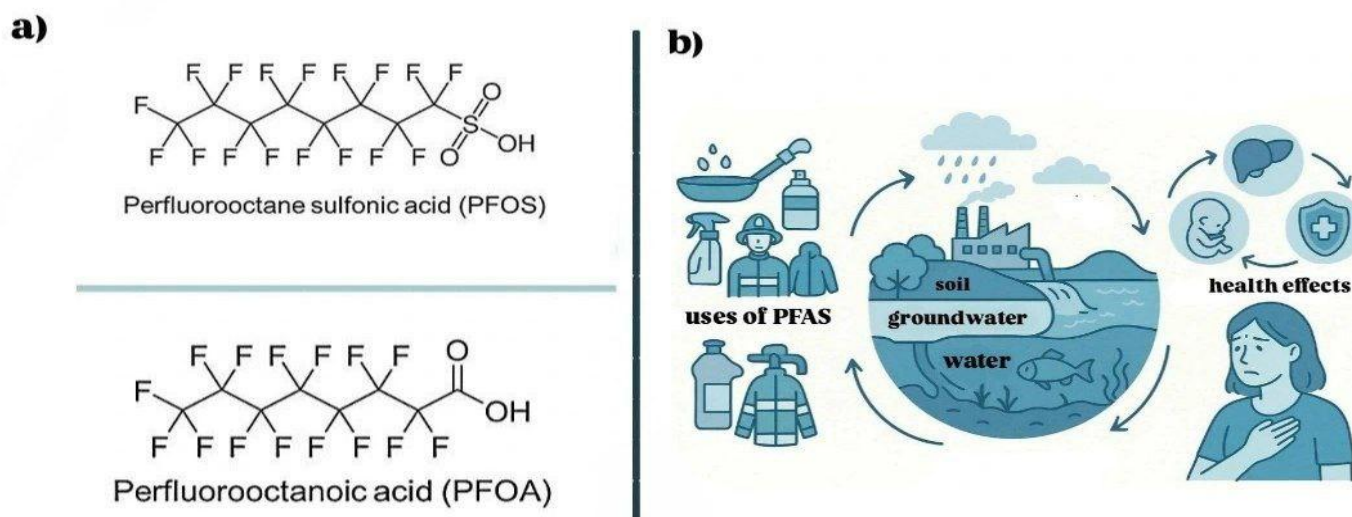


**Figure 1.** (a) The chemical structure of PFOS and PFOA compounds, and (b) the water pollution cycle with PFAS.

Traditional techniques for treating water and wastewater, including coagulation, filtration, aeration, oxidation, and disinfection, are largely ineffective at eliminating perfluoroalkyl acids (PFAAs) because these compounds are highly stable and resistant to breakdown (Kordbacheh and Heidari 2023). Adsorption is distinguished among treatment methods for its superior efficacy in removing organic and inorganic contaminants from water. In this technique, target molecules or ions adhere to the surface of a solid material known as the adsorbent (Gama et al. 2022)(Zare et al. 2018),(Zareitalabad et al. 2013). This method is preferred because it has a simple design, is easy to operate, can treat a wide number of substances, and is moderately cheap. The performance of adsorbents in terms of cost can be classified into three levels: below \$15 per gram, which is a low cost; between \$1 per gram and \$200 per gram, which is an optimal cost; and above \$200 per gram, which is considered a high cost (Ighalo et al. 2022). Although the potential of all materials to adsorb different types of contamination was examined, 2D materials have received close attention in recent years due to their Special properties and superior performance. Section 3 provides background on the six selected 2D materials investigated here.

The widespread occurrence of PFAS worldwide has led governments to prioritize regulating their release into the environment (Lendewig et al. 2025). Due to environmental concerns, there are now limits on how PFAS can be produced and released. The Stockholm Convention limited

the use of PFOS and its derivatives, and PFOA and similar chemicals are being phased out over time (Mudlaff et al. 2024). For safety reasons, industrial chemicals manufactured or imported in quantities exceeding one ton per year should be tested. Such tests shall verify that the chemical does not have a tendency to accumulate in living organisms through a process called bioaccumulation. One of the most important steps in this determination is the measurement or estimation of the chemical's log KOW (Octanol/Water Partition Coefficient) as outlined under the Stockholm Convention (Gimeno et al. 2024).

This paper explores the utilization of 2D materials for the adsorption-based removal of PFAS from water. It encompasses various materials, including graphene, MXenes, metal organic frameworks, covalent organic frameworks, layered double hydroxides, phosphorene, and hexagonal boron nitride. The main aim of the present work is to provide a critical review of recent research outcomes for the purpose of informing future studies specifically focused on advanced nanomaterial applications for PFAS remediation. This review places great emphasis on the effectiveness of such materials in relation to their interaction with PFAS and the main challenges linked to their use.

## **2. Current situation of PFAS**

### **2.1 Definition and Classification**

PFAS are defined by a special chemical structure known as the perfluoroalkyl group ( $C_nF_{2n+1}$ ), consisting of a carbon chain where fluorine atoms substitute for all the hydrogen atoms (Buck et al. 2011). These substances can be divided into numerous classes based on their chemical structures and properties (Niegowska et al. 2021). The key classification entitled PFAS can be categorized as polymeric or non-polymeric depending on whether their chemical structure includes repeating molecular units. Polymeric PFAS have very long carbon chains and include substances like fluoropolymers and perfluoropolyethers. The well-known examples of this type are polytetrafluoroethylene (PTFE), Fluorinated ethylene propylene (FEP), Perfluoroalkoxy alkane (PFA), and Tetrafluoroethylene (ETFE). On the other hand, non-polymeric PFAS usually have shorter chains, with no more than 13 carbon atoms and may contain side chains. This category includes compounds such as perfluoroalkane sulfonyl fluoride (PASF), perfluoroalkyl iodides (PFAI), fluorotelomers (PFPE), and several types of perfluoroalkyl acids (PFAA), like perfluoroalkyl carboxylic acids (PFCA), perfluoroalkane sulfonic acids (PFSA), perfluoroalkyl phosphonic acids (PFPA), and perfluoroalkyl phosphinic acids (PFPIA) (Buck et al. 2011).

Statistics until the end of 2025 demonstrate a considerable growth in scientific interest in PFAS chemicals. Figure 2 shows the number of publications per year based on the Scopus database by searching the words "PFAS" and "Adsorption" in the field "Article title, Abstract, Keywords".

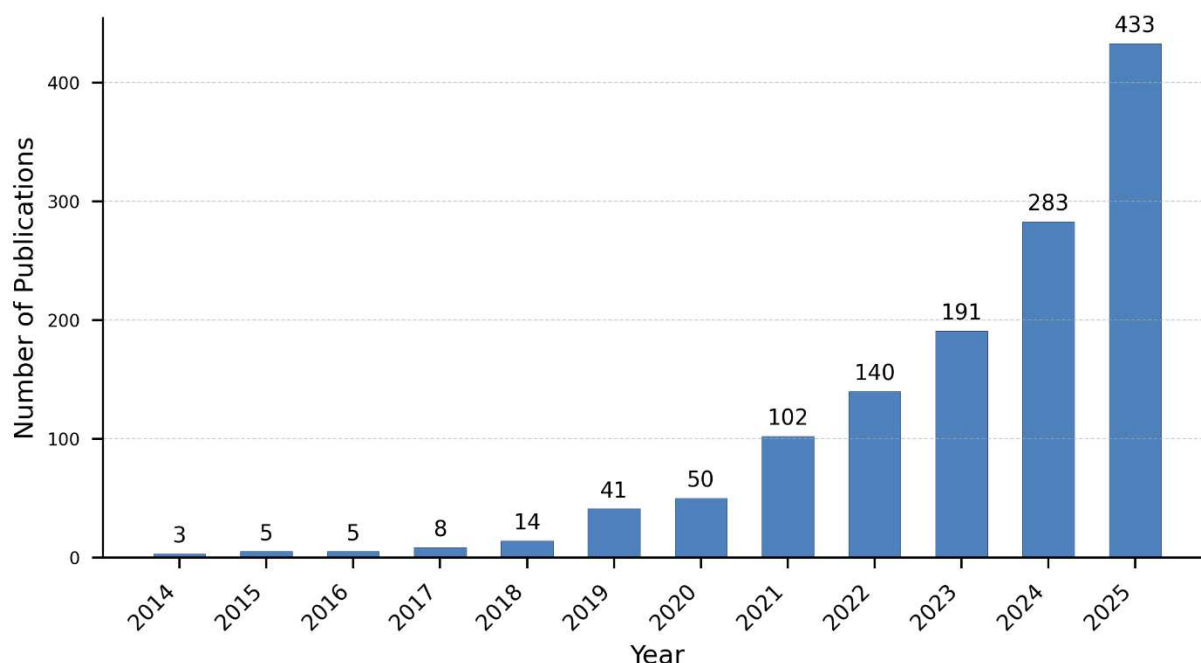


**Figure 2.** The Number of publications per year based on the Scopus database by searching the words "PFAS" and "Adsorption" in the field "Article title, Abstract, Keywords".

## 2.2 Environmental Contamination and Pathways

PFAS pervade the environment directly via manufacturing processes, product utilization, and contaminants, or indirectly through the degradation of PFAS and its precursors. The European Food Safety Authority (EFSA) indicated that certain PFAS exhibit significant resistance to degradation (EFSA et al. 2020), whereas others decompose into very persistent variants, for instance, Fluorotelomer alcohols (FTOHs). These unstable precursors are emitted into the atmosphere or wastewater bodies and undergo oxidation to produce perfluoroalkyl carboxylic acids (PFCAs), particularly PFOA and other  $C_7 - C_{14}$  PFCAs, which are a major source for extensive environmental pollution (Brase et al. 2021). A significant category, the perfluoroalkyl acids (PFAAs), frequently represent the terminal products of PFAS breakdown and are also emitted during the manufacturing and application of certain fluoropolymers (Brendel et al. 2018). Short-chain PFAS and perfluoroalkyl ether carboxylic (PFECAS), previously considered safer alternatives, have been extensively identified in environmental samples due to their solubility in

water and capacity for long-distance transport. Conversely, long-chain PFAS exhibit a greater propensity to adhere to particles and accumulate in organisms over time (Brendel et al. 2018) (Martin et al. 2003) (Ahrens et al. 2010). The pathway by which PFAS enter the environment is illustrated in Figure 3.

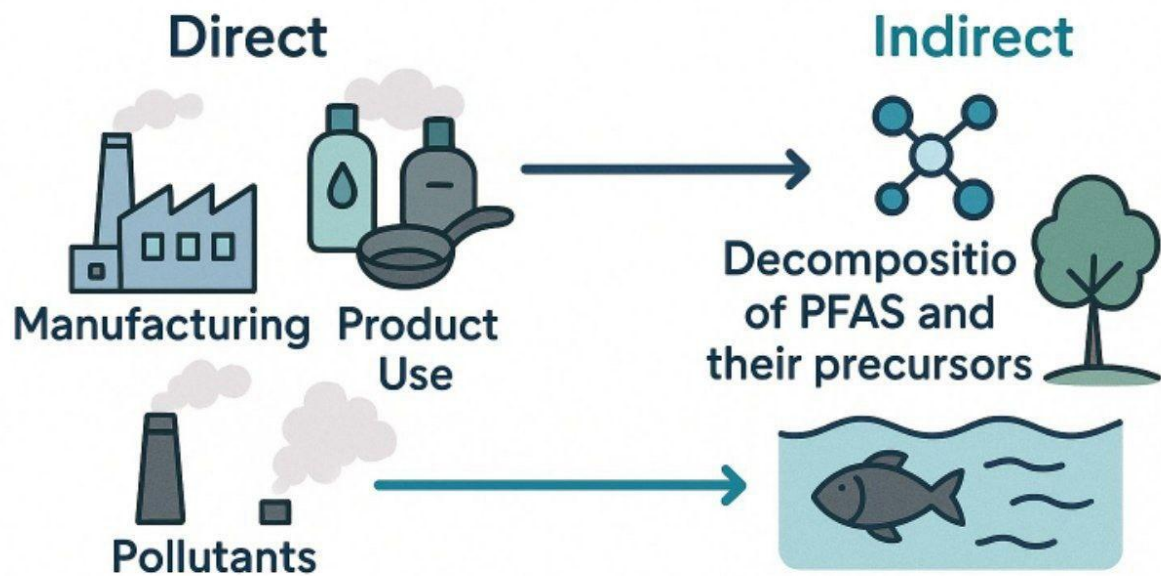


**Figure 3.** Routes of PFAS entry into the environment.

### 2.3 Sources, Industrial Contributions, and Health Implications of PFAS

According to Organization for Economic Cooperation and Development (OECD) data, most PFAS detected in the environment, and living organisms are linear isomers and non-polymeric compounds, often acting as precursors to PFAAs (Goodrum et al. 2021). Some precursors are not directly released into water bodies; for example, 2,3,3,3-Tetrafluoropropene (HFO-1234yf)-a fluorinated refrigerant used as a replacement for the phased-out HFC-134a undergoes atmospheric degradation to form Trifluoroacetic acid (TFA). Though not classified as PFAS, these compounds contribute to environmental contamination, as TFA accumulates in soil and surface waters through precipitation, particularly during rainfall (Freeling and Björnsdotter 2023). Table 1 lists the release of PFAS from different industries along with their effects.

**Table 1.** Release of PFAS from different industries and their effects.

| Industry | Effect(s) | Reference |
|----------|-----------|-----------|
|----------|-----------|-----------|

|                                   |                                                                                                                                                                                                                                                              |                                                                  |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Industrial Facilities             | Major contamination of groundwater and wells near disposal facilities                                                                                                                                                                                        | (Scher et al. 2018) (Davis et al. 2007)                          |
| Firefighting Foams                | Allow PFAS to enter into surrounding soils and waters through leaching and run off, often displaying leaching at significant concentrations                                                                                                                  | (Dauchy et al. 2017) (Høisæter et al. 2019) (Dauchy et al. 2019) |
| Solid Waste Management Facilities | Permit the environmental discharge of PFAS-contaminated leachate via wastewater treatment plants, groundwater infiltration from unlined landfills, unintentional release from landfill liner breaches, and volatile gas emissions through the surface cover. | (ITRC 2020)                                                      |
| Wastewater Treatment Plants       | Wastewater Treatment Plants receive PFAS-laden leachates, and biosolids are often deposited back in landfills, creating a cycle                                                                                                                              | (Meegoda et al. 2020) (Masoner et al. 2020)                      |

Widespread contamination of drinking water with PFAS has been widely reported in the media which indicates the widespread concern in communities affected by such contamination, particularly regarding possible health effects in children and pregnant women. In response, town hall meetings have attracted many community members, who have asked numerous questions about how PFAS contamination may affect their health. Representatives from the Pediatric Environmental Health Specialty Unit (PEHSU) have attended several of these meetings to answer questions about potential risks of PFAS exposure for pregnant women, fetuses, and infants, including possible exposure through breast milk (Anderko et al. 2025).

In the United States, concern over PFAS hazards grew following a 2003 report by the Centers for Disease Control and Prevention (CDC), which revealed that about 98% of Americans carried PFOS in their blood (Calafat et al. 2007)(Lewis et al. 2015). Following research conducted from 2013 to 2014 indicated that, despite the passage of a decade, Americans remained

considerably exposed to PFOS, PFOA, Perfluorononanoic Acid (PFNA), and PFHxS. Studies involving animal and human studies have linked exposure to PFOS and PFOA to a variety of health problems, including hypercholesterolemia, thyroid disease, pregnancy-induced hypertension, ulcerative colitis, and cancer (Barry et al. 2013)(Darrow et al. 2013). Children appear to be especially susceptible. One comprehensive review concluded that exposure to these chemicals in early life may result in increased serum cholesterol levels, reduced immune responses (including antibody responses to vaccines), reduced kidney function, and earlier age of puberty onset in girls (Rappazzo et al. 2017).

In response to the increasing worldwide concern regarding the persistence of PFAS in the environment and their potential health risks, large manufacturers such as 3M and DuPont initiated a voluntary phase-out of the production of PFOS and PFOA in the early 2000s. This industrial phase-out was reflected by a quantified decline in the amounts of PFOS and PFOA present in the blood of the U.S. population (Kato et al. 2011)(Sunderland et al. 2019). However, although the amounts of PFOS and PFOA in the blood of the U.S. population are quantified to decline as a result of this industrial phase-out, these two compounds are still considered to be highly persistent within the environment as a result of their chemical stability (Brennan et al. 2021)(Shin et al. 2011). After older PFAS compounds were no longer made, companies produced new ones, like short-chain PFBS and long-chain GenX, which is used in place of PFOA in production. These alternatives were initially assumed or marketed to be less bioaccumulative in humans due to their shorter biological half-lives compared with legacy long-chain PFAS (Conder et al. 2008).

## **2.4 Regulatory Actions and Global Responses**

In the early 2000s, as scientific and public understanding of PFAS-related health risks improved, many guidelines, legislation, and regulations were enacted to address the problem. As a result, the major manufacturers began voluntarily reducing long-chain PFAS production (Brennan et al. 2021). This was reinforced by international agreements aimed at reducing PFAS pollution, as well as additional legislation by some countries and states. In 2016, the U.S. EPA established lifetime health advisory limits for PFOS and PFOA, recommending that towns notify citizens if water contamination exceeded these safety standards (U.S. Environmental Protection Agency (EPA) 2016).

The Stockholm Convention on Persistent Organic Pollutants (POPs), is one of the most important recent international agreements on environmental health and safety. Adopted in 2001

and effective in 2004 (Pietropoli et al. 2024), this convention aims to eliminate or restrict the production and use of hazardous chemicals. In 2009, the conference agreed to prohibit the manufacture and use of PFOS in most applications, officially listing it as a POP under the convention (Pietropoli et al. 2024). The 152 signatories include both industrialized and developing countries across Asia and South America (Henry et al. 2018).

India has never had comprehensive standalone regulations for the control of PFAS, despite having ratified the Stockholm Convention in 2006 (Lee et al. 2025). China, also a party to the convention and one of the world's largest producers and users of PFAS (Chen et al. 2009), restricted the production of PFOS and PFOA in 2011, but continued to allow their use in firefighting foams (Fu et al. 2023). Brazil is one of the nations that has ratified the Stockholm Convention (Henry et al. 2018). Sulfluramid-a pesticide that breaks down into PFOS remains in production and distribution due to a loophole in the convention (Brennan et al. 2021). This compound has been associated with PFOS contamination in soil, vegetation, and coastal waters (Nascimento et al. 2018).

The EU determined via the REACH regulation that the manufacture, utilization, and distribution of PFOA, its salts, and associated chemicals presented significant hazards to human health and the environment (Reinikainen et al. 2024). According to the European Food Safety Authority (EFSA), PFAS chemicals are frequently found in commonly eaten foods such as fish, eggs, and fruits. Therefore, EFSA advised a weekly consumption threshold of 4.4 nanograms per kilogram of body mass for these chemicals (EFSA et al. 2020).

The U.S. EPA managed the PFAS issue under several laws, such as the Toxic Substances Control Act (TSCA), the Safe Drinking Water Act (SDWA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Brennan et al. 2021). The EPA's efforts to control the proliferation of PFAS have focused on PFOS, PFOA, and other PFAS, which have been voluntarily phased out by industry leaders (Brennan et al. 2021).

In July 2020, the U.S. House approved the 2021 National Defense Authorization Act (NDAA), allocating significant financial resources for PFAS-related initiatives, including \$1.5 billion for remediation projects, \$150 million for PFAS treatment research, and \$15 million to sustain the CDC's health impact study at military installations. In that same month, the Food and Drug Administration (FDA) reported that it had reached an agreement with three companies to eliminate the use of 6:2 Fluorotelomer alcohol (FTOH), a PFAS employed for grease resistance in

food packaging. In January 2021, the corporations consented to systematically eradicate these chemicals over a three-year period. The FDA endorsed the agreement to mitigate health risks while maintaining the integrity of food packaging supply networks (Brennan et al. 2021), as shown in Figure 4 (a) international and national regulations on PFAS and (b) national legislation.

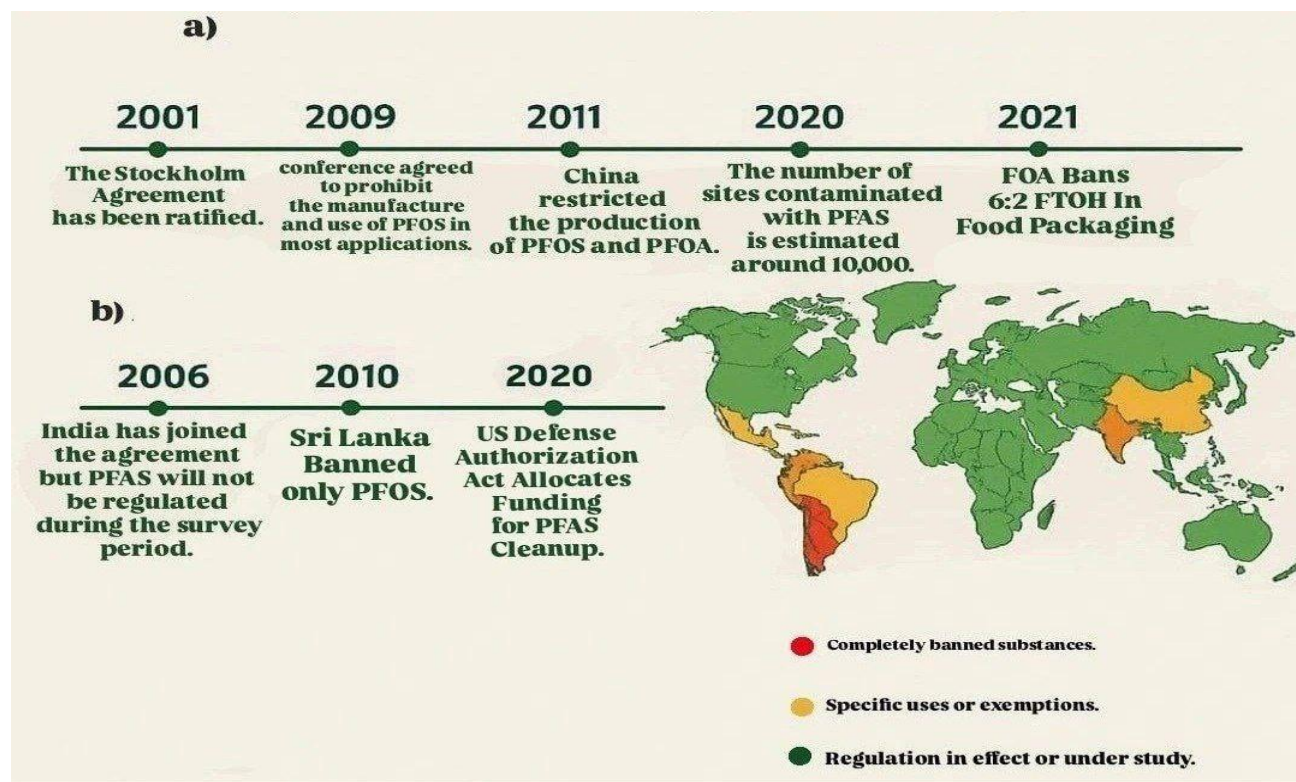


**Figure 4.** (a) International and National Regulations on PFAS and (b) National legislation

### 3. Selected 2D materials

The emergence, development, or modification of 2D materials has received very high attention in the field of water treatment in recent years due to their unique physical and chemical properties, including their elevated surface area, which makes them a promising approach in removing various pollutants from water, especially PFAS compounds. The advantages and disadvantages of 2D materials techniques for PFAS treatment are displayed in Table 2.

**Table 2.** Advantages and disadvantages of 2D materials techniques for PFAS treatment.

| 2D materials | Advantages          | Disadvantages                    | Reference     |
|--------------|---------------------|----------------------------------|---------------|
| Graphene     | -High surface area. | -Low efficiency with short-chain | (Mahpishanian |

|                                    |                                                                                                                                                |                                                                                                                                                                         |                                             |
|------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|
|                                    | -It can be altered to attain a positive charge.                                                                                                | PFAS compounds.                                                                                                                                                         | et al. 2024)                                |
| MXenes                             | -Amino groups may be included to augment electrostatic interactions.                                                                           | -Prone to aggregation, which diminishes efficacy unless enhanced formulations are developed.<br><br>-Extremely responsive to environmental factors, including pH levels | (Liu et al. 2022)<br>(Shrestha et al. 2024) |
| 2D Metal-organic frameworks (MOFs) | -Unique structural advantage.<br>-Fast sorption kinetics.                                                                                      | Low acid stability.<br>- Limited commercial availability and cost consideration compared to other absorbent materials.                                                  | (Chen et al. 2016)                          |
| Covalent organic frameworks (COFs) | -The accurate crystal structure facilitates effective clustering.                                                                              | -The presence of additional contaminants affects efficiency.                                                                                                            | (Zarei et al. 2025)                         |
| Layered double hydroxides (LDH)    | -Efficient elimination of some PFAS chemicals, even at minimal concentrations.                                                                 | -Limited removal without modification.<br><br>-Decreased efficiency in the presence of competitive anions.                                                              | (Kim et al. 2024)                           |
| Phosphorene                        | -Enhanced performance upon the introduction of crystalline defects (SV/DV).<br><br>-Theoretically computed via Density Functional Theory (DFT) | -Insufficient empirical research                                                                                                                                        | (Liu et al. 2020)                           |
| Hexagonal boron nitride (h-BN)     | -Stable in terms of thermal and chemical properties                                                                                            | -Insufficient empirical research                                                                                                                                        | (Feng et al. 2016)                          |

### 3.1. Graphene

Graphene consists of single layer carbon atoms arranged in a hexagonal pattern, making it the only naturally occurring 2D crystal. Its exceptional electronic and optical properties stem from its structure, including surface ripples that influence conductivity (Yildiz et al. 2021). Graphene boasts a range of applications due to its mechanical strength, light weight, and chemical flexibility—mostly in sensors and energy storage devices (Banerjee et al. 2015).

The carbon atoms in graphene are prone to chemical reactions from every end because of its monolayer structure and  $sp^2$  hybridization. The nature of graphene makes it a substance that is chemically active and can be transformed into certain configurations (Potts et al. 2011). Graphene oxide has a negatively charged surface that repels specific contaminants such as PFOA (Mahpishanian et al. 2024), but this substance is limited in removing short-chain PFAS (Wang et al. 2023). Recently, graphene oxide (GO) has attracted considerable interest as a material for wastewater treatment due to its large surface area and abundant oxygen-containing functional groups, including hydroxyl, carboxyl, and epoxy groups (Hussain and Maktedar 2023). Graphene oxide-based materials have recently shown promising performance for the removal of PFAS from water (Bresnahan et al. 2023). However, GO is negatively charged, and its hydrophilic nature limits the adsorption of anionic PFAS. Hence, modification in the structure of GO is a prerequisite for GO to be used as an adsorbent for PFAS. Figure 5 shows graphene lattice structure.

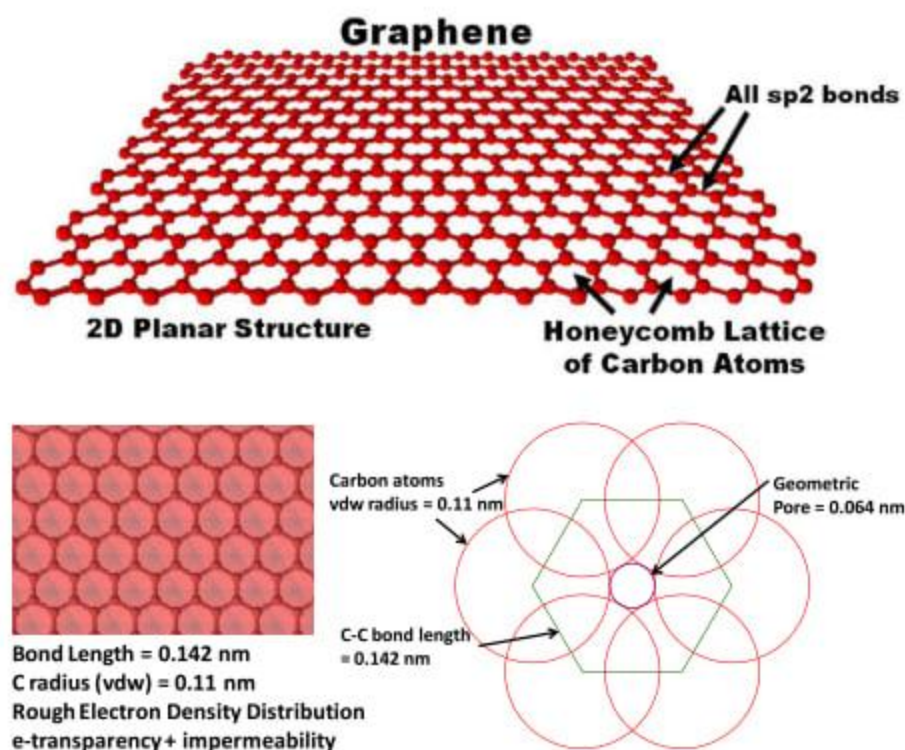


**Figure 5.** Graphene lattice structure:  $sp^2$  hybridized carbon atoms arranged in a 2D honeycomb lattice. (Bottom) the molecular structure with rough electronic density distribution: while graphene is relatively transparent to electrons, it is practically impermeable to all molecules at room temperature. The geometric pore (0.064 nm) is also small enough not to allow molecules to pass through (Berry 2013).

### 3.2. MXenes

Until today, MXenes are considered as a new family of 2D nanomaterials consisting of combinations of transition metal nitrides, carbides, or carbonitrides. These are defined with the general formula  $M_{n+1}X_nT_x$ , where  $n = 1-3$ . They feature early transition metals such as titanium and niobium, X is carbon or nitrogen, and T stands for surface functional groups including hydroxyl, oxide, or fluoride (Manasa and Rout 2023).

Among the prominent members of MXenes,  $Ti_3C_2T_x$  has attracted a focus on water purification and environmental remediation due to its large surface area, high conductivity, and non-toxic degradation products (Manasa and Rout 2023)(Zhang et al. 2024). These materials have started showing an upward trend in their effectiveness as adsorbents and catalysts through the

capture of ions and selective adhesion on contaminants (Alyasi et al. 2024). Figure 6 shows crystal structures of 2D  $M_2X$  MXenes.

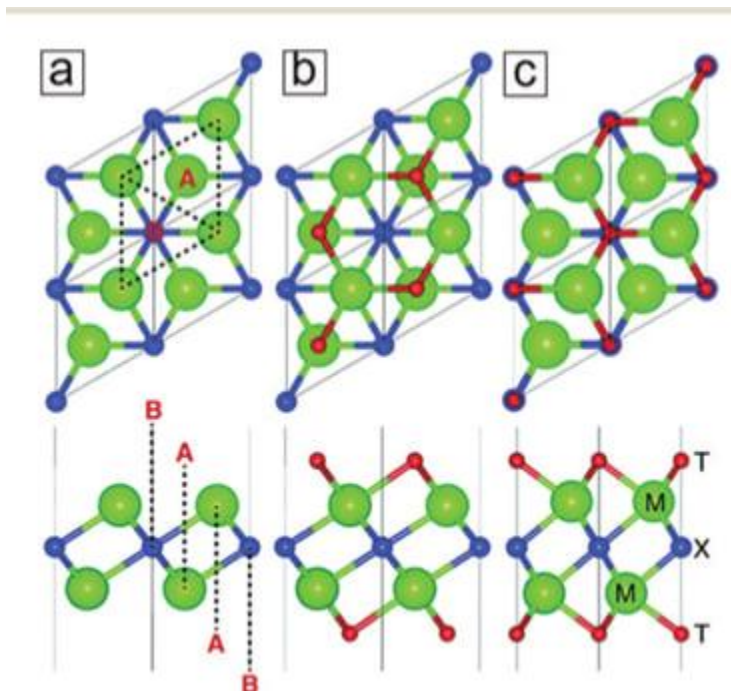


**Figure 6.** Crystal structures of 2D  $M_2X$  MXenes. (a) The  $Ti_2C$  MXene model comprises a rhombus unit cell (dashed line) with hexagonal symmetry (top view). It consists of trilayer configurations where the C atomic layer is sandwiched between two Ti atomic layers (bottom panel). (b and c) MXene models with two different surface termination group configurations (Khazaei et al. 2017).

Despite their significant potential, previously only around 30 MXene variants have been developed and studied, implying that numerous undiscovered forms with distinctive characteristics may exist. In addition, like graphene, MXenes have proven effective in hydrogel formation, further extending their versatility and application scope (Hussain and Maktedar 2023). Currently >40 MXene compositions exist. The ultimate number is far greater and in time they may develop into the largest family of 2D materials known. MXenes (Ayodhya 2023)(Anasori et al. 2015).

### 3.3. 2D Metal-Organic Frameworks

Generally, MOF metal complexes often possess three coordination sites, enabling the formation of 2D structural networks. (Kurth and Higuchi 2006)(Spokoiny et al. 2009). 2D MOFs

represent a recent class of materials featuring excellent electrical conductivity, customizable chemical properties, high porosity, well-defined crystallinity, notable mechanical stability, and efficient photocatalytic activity (Sun et al. 2016)(Li et al. 2017), (Mortazavi et al. 2019),(Myakala et al. 2024), as shown in Figure 7. They often feature structural networks with three, four, or six connectivity points (Yang et al. 2011).

2D MOFs are highly valued due to their unique properties, including tunable pore architectures and large surface areas (Paquin et al. 2015). One key benefit is the ability to embed a wide range of functional groups on the framework without disrupting its original structure. Further, their regular porosity and ordered topology make them highly versatile materials for advanced applications (Evans et al. 2014). Like most 2D materials, preparation of 2D MOFs can be accomplished by using either the top-down or the bottom-up strategies, or both. The top-down approach is based on the exfoliation of layered MOFs under physical or chemical conditions, while the bottom-up strategy involves directly generating the 2D MOF nanosheets from the building blocks-metal ions and organic linkers-during the synthesis process (Huh et al. 2010), (Zhao et al. 2018) (Shi et al. 2021) (Duan et al. 2020).

ZIF-L(2D MOF) was synthesized by adding 1.488 g (4.85 mmol) of zinc nitrate ( $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ , 98%) to 25 mL of diethylformamide (DMF) (Chen et al. 2016). In a separate solution, 2.3628 g (24.2 mmol) of benzimidazole (BEL) ( $\text{C}_7\text{H}_6\text{N}_2$ , 98%) and 1.3602 g (24.2 mmol) of sodium formate ( $\text{HCOONa}$ , 99%) were added to 50 mL of methanol. The material was then separated by centrifugation and washed three times with methanol. The final product was oven-dried at 105°C before use, with each batch yielding approximately 0.2 grams. ZIF-L, which features a layered 2D structure composed of zinc and 2-methylimidazole, exhibits remarkable adsorption performance.

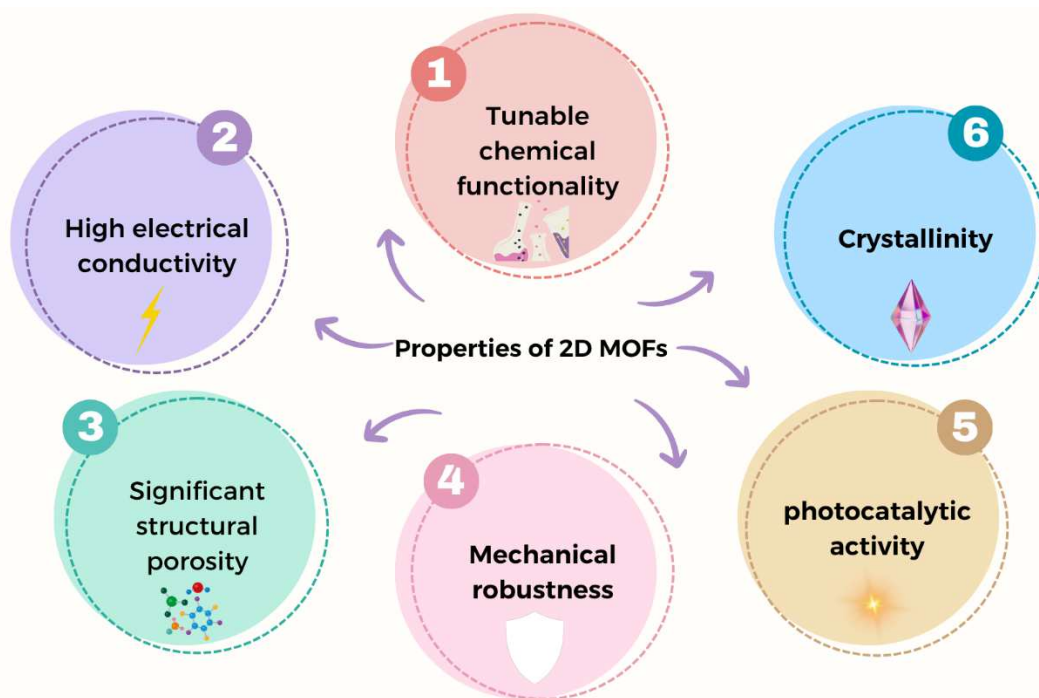


**Figure 7.** Some key properties of 2D MOFs.

### 3.4. Covalent Organic Frameworks

COFs represent a relatively new type of crystalline material noted for their stable porosity, lightweight structure, and exceptional durability against heat and chemical attack (Arqueros et al. 2021). These structures are formed by connecting organic units using reversible covalent bonds (Arqueros et al. 2021)(Lohse and Bein 2018). Maintaining stability in aqueous chemical conditions is essential for water treatment purposes (Xia et al. 2021). The early kinds of COFs that were prepared using boroxine and boronate ester chemistry possessed weaknesses under moist conditions (Côté et al. 2005)(Côté et al. 2007). 2D COFs are typically synthesized from organic building blocks within closed reaction systems via solvothermal methods, where the reaction occurs gradually under moderate conditions. The framework develops concurrently with crystallization, and reversible bond formation facilitates self-healing, thereby minimizing defects and yielding thermodynamically stable ordered structures (Côté et al. 2005). In recent years, ionothermal (Kuhn et al. 2008), mechanochemical (Biswal et al. 2013), and microwave-assisted syntheses (Campbell et al. 2009) have emerged as alternative methods for the preparation of COFs; however, these techniques typically demonstrate inferior crystallinity, reduced reproducibility, and narrower applicability in comparison to solvothermal approaches, which continue to be the

predominant method for generating highly crystalline frameworks. Challenges remain in streamlining preparation methods and improving the structural integrity and application efficacy of 2D conjugated COFs for practical applications (Zhang et al. 2022). Figure 8 shows illustrative diagrammatic comparison of 2D conjugated COFs constructed by conventional methods and the “two-in-one” strategy.

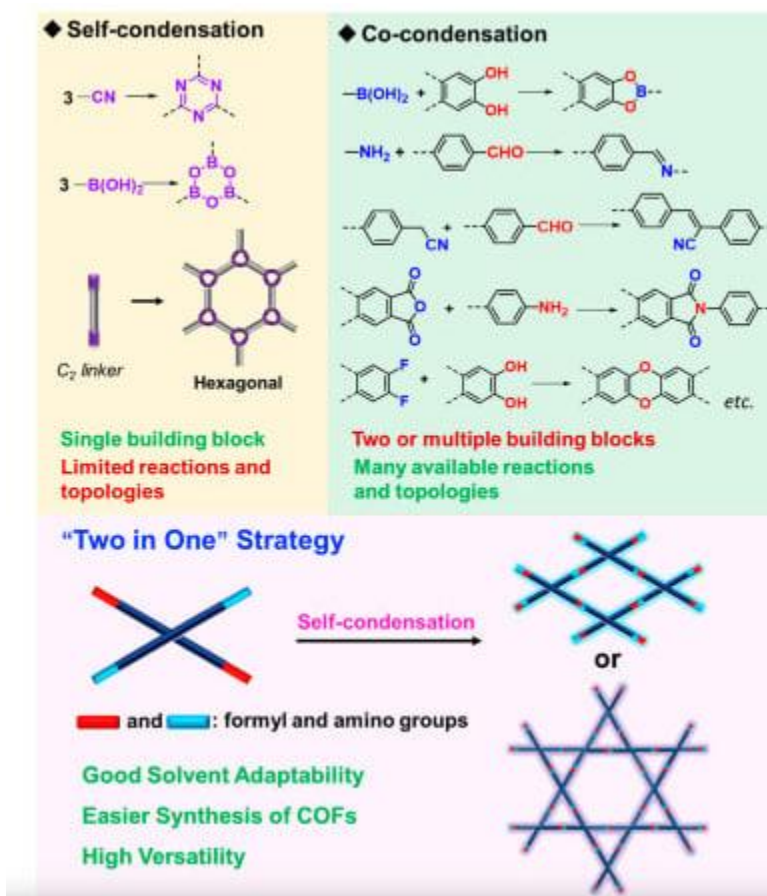


**Figure 8.** Illustrative diagrammatic comparison of 2D conjugated COFs constructed by conventional methods and the “two-in-one” strategy (Li et al. 2019).

The point that makes ketoenamine-linked COFs stand out is their outstanding chemical stability under both acidic and basic conditions, which greatly expands their possible applications. To achieve the goal of improving their chemical stability, some synergistic strategies have been explored, including the introduction of certain functional groups, such as methoxy or hydroxy groups, into the organic linkers of COFs (Li et al. 2019)(Kandambeth et al. 2018). On the contrary, one significant challenge toward practical applications of COFs is their limited processability

because COFs are often obtained as insoluble powders. The ability to shape COFs into functional forms is essential for using them (Carrington et al. 2022)(Rodríguez-San-Miguel 2019). Figure 8 shows a schematic representation of COF evolution and application

### 3.5. Layered Double Hydroxides

LDHs are known for being good for the environment, having a wide surface area, being able to exchange ions well, and being able to be reused for many adsorption cycles (Johnston et al. 2021). LDHs are used in a lot of ways, including medicine administration, catalytic processes, flame retardants, medical devices, polymer enhancement, and cutting-edge water-splitting technologies (Mureseanu et al. 2022) (Kostić et al. 2022) (Guo et al. 2021). Figure 9 shows a schematic illustration of LDH structure and chemical components

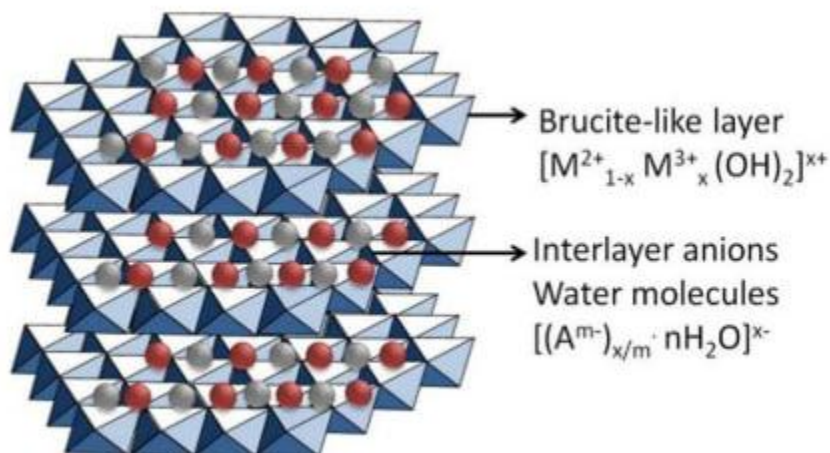


**Figure 9.** Schematic illustration of LDH structure and chemical components (Gu et al. 2015).

These materials feature 2D nanostructures consisting of alternating divalent and trivalent metal hydroxide layers, with interlayer spaces occupied by water and anions (Velusamy et al. 2021). LDHs also have a strong, brucite-like framework made up of metal hydroxide octahedra that share edges. This structure is similar to that of graphene oxide nanosheets (Gabriel et al. 2022).

### 3.6. Phosphorene

Phosphorene represents another class of 2D p-type materials that possess high flexibility and can be easily mechanically exfoliated (Liu et al. 2014), similar to graphene. These properties support the growing interest in the field of 2D layered materials showing improved mechanical, electrical, and optical performances compared to their bulk counterparts and possessing a

remarkable potential for future technological applications beyond conventional silicon-based devices (Kassem 2013)(Fang et al. 2013). The bulk counterpart of phosphorene, the so-called black phosphorus, is the most stable form of phosphorus at room temperature (Warschauer 1963)(Nishii et al. 1987). Figure 10 shows a structure of phosphorene.

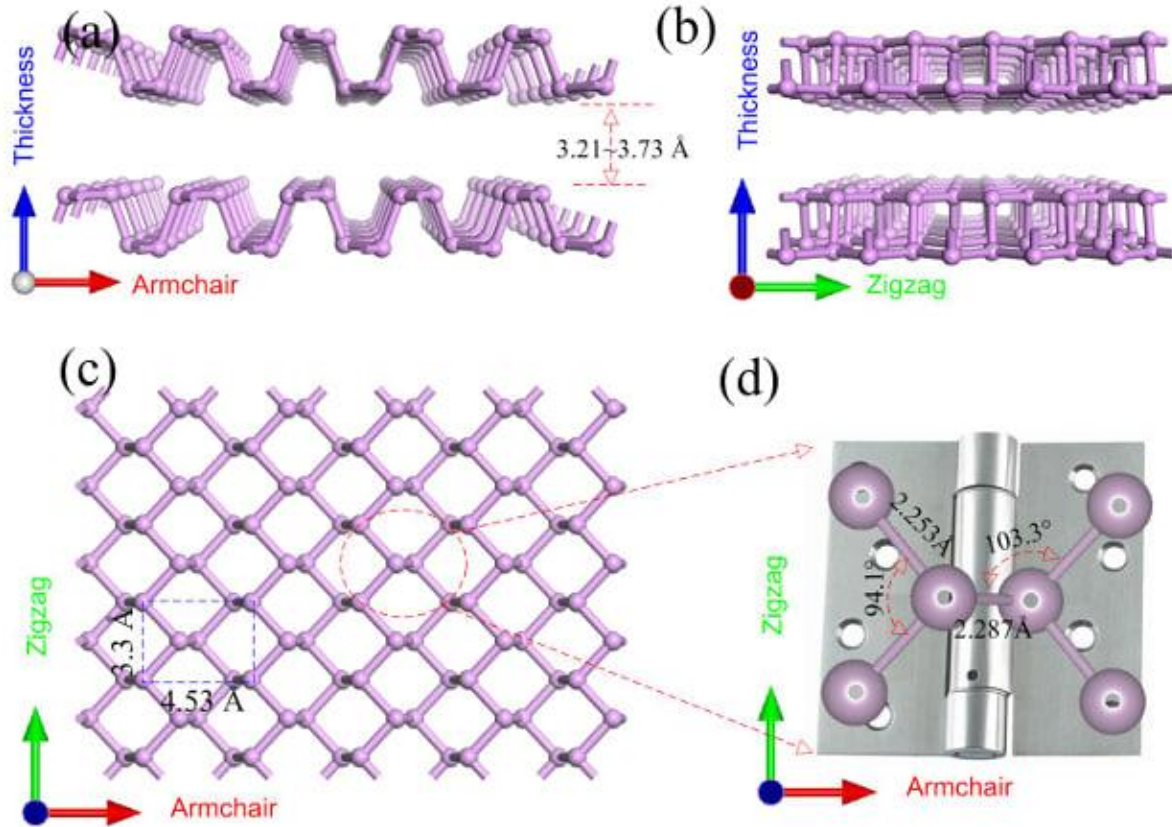


**Figure 10.** Structure of phosphorene: (a,b) side views from the zigzag and the armchair direction, (c) top view, and (d) zoomed-in local atomic structure of the P-P bonding configuration, where each phosphorus atom is bonded with three adjacent phosphorus atoms, forming a puckered structure, which resembles a network of connected hinges that exhibits anisotropic rotational deformation under strain. The different bonding arrangements along the armchair and zigzag direction are the origin of the intrinsic anisotropy of many physical and mechanical properties of phosphorene (Kou et al. 2015).

Unlike many other 2D materials, phosphorene has a direct bandgap for all thicknesses that range from a monolayer to its bulk (Qiao et al. 2014) (Zhang et al. 2014). This is opposed to graphene, a semimetal, and transition metal dichalcogenides (TMDs), which only express a direct

bandgap in their monolayer form (Mak et al. 2010)(Ross et al. 2013). The investigation into the optical properties of phosphorene by means of Raman and photoluminescence (PL) spectroscopy is necessary to understand its electronic structure, crystal orientation, and anisotropic behavior of excitons and trions. Excitons are bound states of an electron and a hole through Coulombic attraction, while trions are charged excitons composed of either two electrons and one hole or two holes and one electron (Kheng et al. 1993).

### **3.7. Hexagonal Boron Nitride**

Hexagonal Boron Nitride (h-BN) is highly recognized for its excellent physical, chemical, and mechanical properties (Pakdel et al. 2014). It demonstrates excellent thermal, dielectric, and structural properties, which have made it versatile enough for a wide range of technological applications (Falin et al. 2017). Structurally, it is constructed in a hexagonal lattice with strongly polar bonds between boron and nitrogen atoms, which have usually been analyzed through optical and spectroscopic approaches. These strong B-N bonds provide the material with anisotropic characteristics, high mechanical strength, and good thermal insulation. Such strong covalent interactions provide various forms of boron nitride with remarkable thermal and chemical resistance (Pakdel et al. 2014). Figure 11 shows a) geometrical structure of h-BN; the unit cell is represented in red dash lines. b) displaying the probable atomic distribution of B and N atoms in different orientations; c) illustrations showing possible configurations that can be derived using h-BN

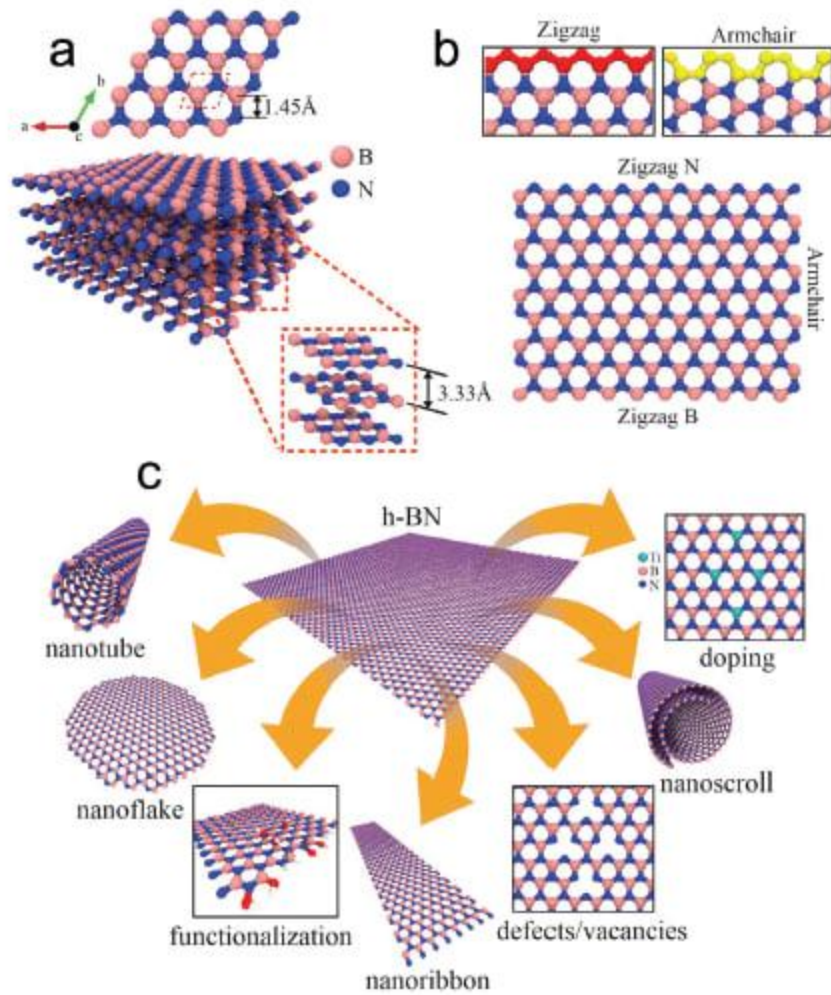


**Figure 11.** a) Geometrical structure of h-BN; the unit cell is represented in red dash lines. b) Displaying the probable atomic distribution of B and N atoms in different orientations; c) Illustrations showing possible configurations that can be derived using h-BN (Roy et al. 2021).

2D h-BN is a potential future technology in graphene electronics in terms of stability and efficiency (Meric et al. 2013). In contrast to graphene, h-BN possesses a bandgap of 5-6 eV, which can be modified through edge passivation using foreign atoms, especially those with improved heat and chemical stability, oxidative resistance, or favorable optical properties (Gao et al. 2009)(Wang et al. 2011),(Azamat et al. 2016). For these reasons, h-BNs are considered a potential material in optoelectronics, field-effect transistors, catalysis, tunneling, and water treatment technologies (Neek-Amal et al. 2013).

## 4. Removal of PFAS using 2D materials

### 4.1. Graphene

GO is among the limited number of 2D materials utilized in practical applications, thanks to its extensive surface area and abundant oxygen-functional groups including hydroxyl, carboxyl, and epoxy groups (Velusamy et al. 2021)(Pervez et al. 2023). It has gained popularity for wastewater purification. Moreover, recent research indicates that GO is a promising material for eliminating PFAS from polluted water (Bresnahan et al. 2023)(Wang et al. 2023).

GO has potential, but its ability to absorb negatively charged PFAS is limited by its negatively charged and hydrophilic surface (Pervez et al. 2024). Adding the positively charged polymer polyethylenimine (PEI) improved the adsorption of PFOA, which had a capacity of roughly 368.2 mg/g. Tian et al. (Tian et al. 2021) similarly showed that the modification of GO with ethylene diamine greatly enhanced its PFOA adsorption capability to 1575 mg/g (Yu et al. 2009)(Du et al. 2015).

Various types of graphene oxide-based adsorbents have been developed by researchers, out of which GO-CTAC (the one modified with cetyltrimethylammonium chloride) showed the best performance for PFAS removal from aquatic media. The characterization results indicated that cetyltrimethylammonium chloride (CTAC) had successfully been loaded onto the surface of GO without any change in its properties. Meanwhile, the addition of CTAC caused a very highly positive surface charge of the GO-CTAC adsorbent, thus playing a critical role in the adsorption efficiency. Accordingly, it was observed that the GO-CTAC adsorbent captured almost 100% of target PFAS in pure water within 30 seconds of contact time. The performance of GO-CTAC for the removal of PFAS, except for PFBA, was not affected much by variations in pH, NOM concentration, and ionic strength. Figure 12 shows the mechanism of PFAS removal using GO-CTAC (Pervez et al. 2024). The illustration shows the adsorption process of PFAS onto the surface of CTAC-modified graphene oxide (GO-CTAC), where pollutants are removed from the aqueous solution through electrostatic and hydrophobic interactions. The process achieves up to 100% removal efficiency for 11 PFAS compounds within a rapid adsorption time (~30 seconds).

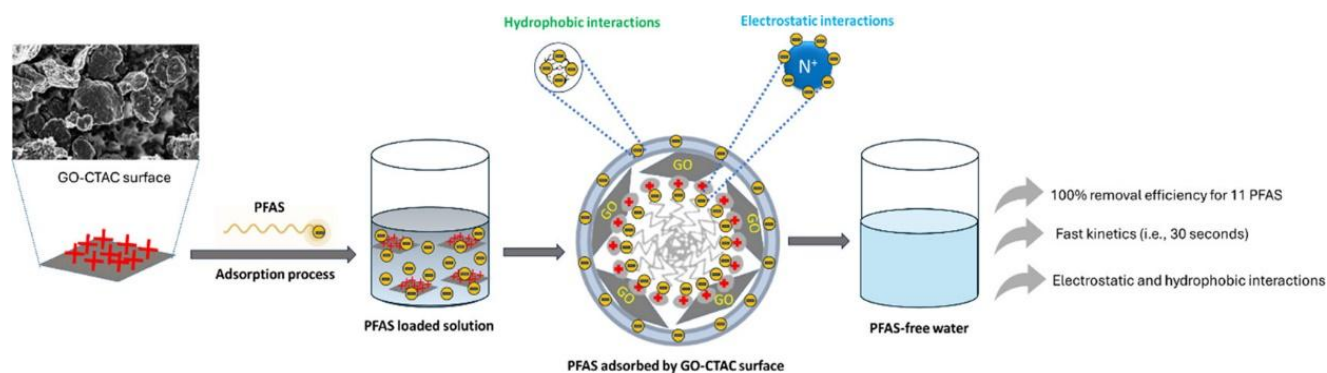


**Figure 12.** Mechanism of PFAS removal using GO-CTAC (Pervez et al. 2024).

In this context, researchers also prepared amino-functionalized graphene oxide (AGO) aerogels as an effective material that can be utilized for the removal of PFOA from contaminated water. Five operating parameters were optimized in order to identify optimal conditions for adsorption: contact time, concentration, pH, adsorbent dosage, and temperature. It was determined that the PFOA adsorption followed the pseudo-second-order kinetics, with a better efficiency at low pH values and the adsorption equilibrium being reached after 48 h. The Freundlich isotherm model best fitted the adsorption behavior, while further analyses using the Dubinin Radushkevich (D-R) isotherm and thermodynamic parameters investigated that the process was physical, exothermic, and spontaneous in nature, as depicted by Figure 13. The AGO aerogels showed a very high adsorption capacity of 1575 mg/g for PFOA (Dayong et al. 2021).

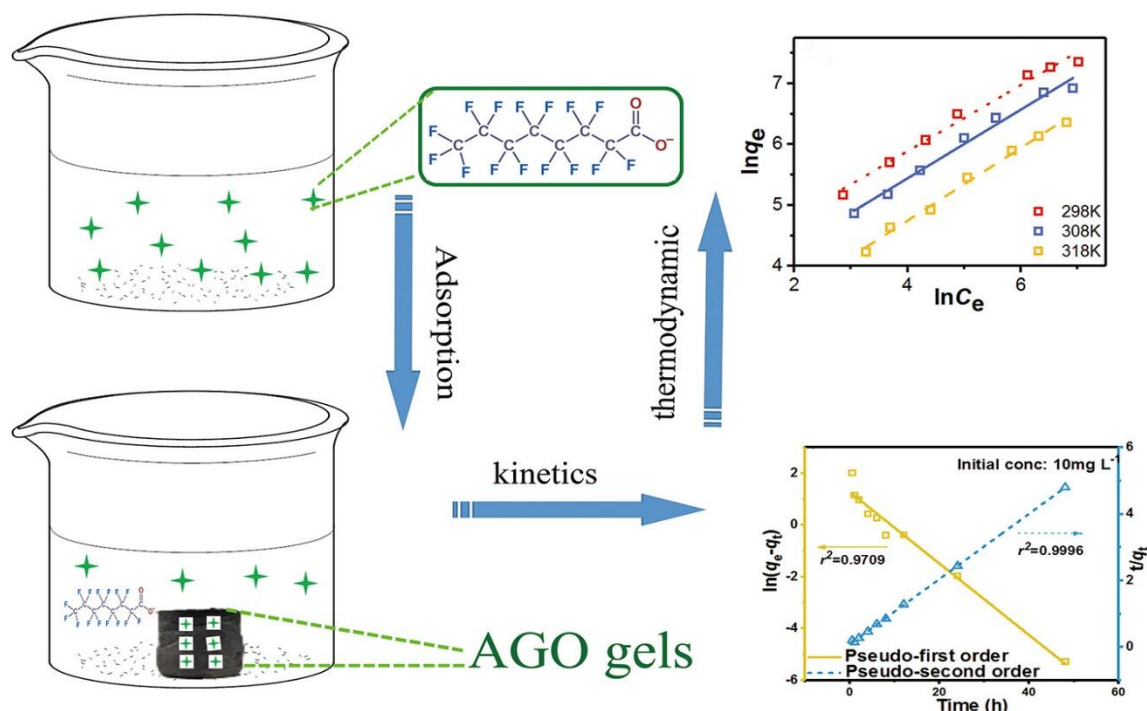


**Figure 13.** Efficient removal of PFOA using amino-functionalized graphene oxide aerogels (Dayong et al. 2021). The adsorption kinetics and isotherm of PFOA were well-fitted using pseudo-second-order and the Freundlich modelling. The adsorption mechanism of PFOA onto AGO aerogels followed spontaneous, exothermic, and physical processes.

One earlier study explored a new nano-adsorbent by incorporating iron oxide NPs into amine-functionalized graphene oxide, producing magnetic MAGO. This material was tested for its performance in removing PFOA, PFOS, and PFHxS from water. The findings revealed that the amine groups played a crucial role in attracting negatively charged PFAS, especially short-chain ones, through electrostatic interactions. However, the addition of amine groups and iron oxide slightly decreased the colloidal stability of the material. Kinetic study showed that the adsorption process followed most closely the pseudo-second-order model and occurred in three stages: a fast initial uptake, a slower middle phase, and equilibrium reached within 30 min (Mahpishanian et al. 2024). Table 3 shows recent studies that used graphene to adsorb PFAS.

**Table 3.** Some recent studies have used graphene to adsorb PFAS.

| Adsorbent Materials | Type of PFAS | Capacity (mg/g) | Concentration (mg/L) | pH | Time (h) | Removal Efficiency (%) | Reference |
|---------------------|--------------|-----------------|----------------------|----|----------|------------------------|-----------|
|---------------------|--------------|-----------------|----------------------|----|----------|------------------------|-----------|

|                     |                                                                                                     |        |           |     |             |            |                               |
|---------------------|-----------------------------------------------------------------------------------------------------|--------|-----------|-----|-------------|------------|-------------------------------|
| GO-CTAC             | PFHxS,<br>PFOA,<br>6:2 FTSA,<br>PFOS,<br>PFNA,<br>PFDA,<br>PFHpA,<br>PFBA,<br>GenX,<br>PDDA<br>PFBS | 48.47  | 0.02      | 8   | 0.01        | ~100       | (Pervez et al.<br>2024)       |
| GO-DMEN             | PFBA,<br>PFPeA,<br>PFBS,<br>PFHxA,<br>PFHpA,<br>PFHxS,<br>PFOA,PFNA                                 | 0.0026 | 0.0005    | 7   | 0.25        | up to 98.0 | (Trifoglio et<br>al. 2025)    |
| GO                  | PFAS                                                                                                | -----  | 0.005-0.5 | 4-7 | 0.5         | >95.0      | (Mahpishanian<br>et al. 2024) |
| GO-PEI3             | PFOA                                                                                                | 368.2  | 10-100    | 4   | 5           | 100.0      | (Lei et al.<br>2022)          |
| CS-GO (10:1)        | OBS                                                                                                 | 3260   | 50        | 3   | 2           | up to 95.4 | (Lu et al.<br>2024)           |
| PAGO                | PFOA                                                                                                | 2180   | 10        | 7   | 0.016       | >99.0      | (Xu et al.<br>2025)           |
| FGO-PEI             | PFNA                                                                                                | ~219   | 1         | 7   | 4           | 100.0      | (Pramanik et<br>al. 2023)     |
| Cu/F-rGA(+0.8<br>V) | PFOA                                                                                                | -----  | 1         | 6   | 10<br>times | 75.5       | (Liu et al.<br>2021)          |

Graphene-based materials feature huge potential for PFAS removal during water treatment because of their distinctive surface characteristics. GO-DMEN showed a maximum removal efficiency of 98% with very low concentrations, hence being suitable for trace-level PFAS treatment, though its low adsorption capacity may reduce the effectiveness with higher contaminant loads or multiple cycles. Among them, MAGO was exceptional for its high efficiency maintained in a wide pH range of 4-7, indicating strong adaptability. GO-PEI3 showed excellent performance in the laboratory with an elevated capacity of 368.2 mg/g and 100% removal at pH 4; however, its efficiency may decline under real conditions. CS-GO (10:1) demonstrated the highest adsorption capacity among these materials with a value of 3260 mg/g and a corresponding removal rate of 95.4%, though its optimal function at pH = 3 may limit its field application. In contrast, PAGO combined strong adsorption capacity with elevated efficiency at neutral pH, hence being more practical. FGO-PEI achieved 100% removal at pH = 7 under low PFAS concentration conditions, and its capacity was just average compared to that of several options. Cu/F- rGA (+0.8 V) is a copper and fluorine-modified reduced graphene material that was operated with an applied voltage and utilizes an electrochemical adsorption process. It had a good performance near the natural pH of  $6.00 \pm 0.10$  and is reusable, indicating good chemical durability; however, the removal efficiency is far behind that compared to other materials.

## **4.2. MXenes**

In recent years, MXenes have cropped up as promising adsorbents owing to their distinct structural and physicochemical properties. One important feature of MXenes that can enhance their ability to adsorb is the high surface area (Feng et al. 2022)(Jatoi et al. 2023). In addition, their surfaces can be readily functionalized with different chemical groups; this increases their ability to adsorb contaminants by providing attachment sites (Solangi et al. 2023). One of the main characteristics of MXenes in the adsorption process involves their possibility of remaining chemically stable and being able to vary their composition. They maintain their structure even at variations of pH and thus ideal for a number of applications ranging from environmental (Jatoi et al. 2023)(Liang et al. 2023),(Iravani 2022).

Other researchers (Shrestha et al. 2024) fabricated the composite MXene-PEDOT:PSS and used acid etching to remove excess PSS, thereby increasing the composite's porosity and interlayer spacing. Characterization through Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Fourier Transform Infrared Spectroscopy (FTIR), and X-ray Diffraction

(XRD), validated the enhanced structural and surface properties of the acid-etched composite (AE-MP). A fourfold enhancement in the volumetric capacitance after treatment was evidenced by cyclic voltammetry, with an optimal 5 wt% loading of Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) PEDOT: PSS. Electrosorption experiments were conducted using a solution containing perfluorohexanoic acid (PFHxA), PFOA, and PFNA at a concentration range from 100 to 750 ppb, which resulted in adsorption capacities as high as 54.9 mg/g at +1.0 V. The study further revealed reversible PFAS desorption upon application of a negative voltage, thus reusing the adsorbent. The kinetics followed the pseudo-second-order model, and a fast adsorption equilibrium was achieved in 240–300 seconds. The reusability was also confirmed during five adsorption-desorption cycles without significant loss in performance.

The mechanism for adsorption is an electro-adsorption method utilizing electrical voltage for attracting PFAS chemicals. The adsorbent MXene-PEDOT: PSS can also reversibly adsorb/desorb PFAS through variation of the applied voltage. The treatment by acid etching increased the specific surface area and pore size and volume of the adsorbent, leading to an approximate 400% increase in volumetric capacitance for PFAS. Adsorption capacities for PFHxA, perfluorooctanoic acid (PFOA), and perfluorononanoic acid (PFNA) were estimated at approximately 45.6, 51.1, and 54.9 mg/g, respectively, for a solution at an initial concentration of 750 ppb under +1.0 V voltage. Adsorbed PFAS can be liberated from the surface by using a negative voltage (Shrestha et al. 2024). The performance of the modified MXenes from the mentioned study is shown in Table 4.

**Table 4.** Performance of the modified MXenes applied to remove PFAS.

| Absorbent Material | Type of PFAS | Capacity (mg/g)/removal | Concentration (ppb) | pH   | Time (s) | Adsorption Rate Constant ( $s^{-1}$ ) | Reference              |
|--------------------|--------------|-------------------------|---------------------|------|----------|---------------------------------------|------------------------|
| MXene-PEDOT:PSS    | PFHXA        | 45.6                    | 750                 | ~6.0 | 240-300  | $1.0 \times 10^{-4}$                  | (Shrestha et al. 2024) |
| MXene-PEDOT:PSS    | PFOA         | 51.1                    | 750                 | ~6.0 | 240-300  | $1.4 \times 10^{-1}$                  | (Shrestha et al. 2024) |

|                                                    |                                      |       |             |      |         |                     |                        |
|----------------------------------------------------|--------------------------------------|-------|-------------|------|---------|---------------------|------------------------|
| MXene-PEDOT:PSS                                    | PFNA                                 | 215.9 | 750         | ~6.0 | 240-300 | $18 \times 10^{-4}$ | (Shrestha et al. 2024) |
| 6:2 fluorotelomer sulfonamidopropyl betaine (FTAB) | Ti <sub>3</sub> C <sub>2</sub> MXene | >80%  | 0.1–10 µg/L | 7    | 1(h)    | ~75 (µg/ng/min)     | (Dixit et al. 2022)    |
| 7:3 fluorotelomer betaines (FTB)                   | Ti <sub>3</sub> C <sub>2</sub> MXene | >80%  | ~1–2 µg/L   | 7    | 1(h)    | -----               | (Dixit et al. 2022)    |

571

572 The adsorption behaviors of PFAS compounds on the MXene-PEDOT: PSS hybrid

573 material showed different trends in regard to the molecular structure of the adsorbate. PFHXA had

574 the minimum adsorption capacity of 45.6 mg/g and an extremely lower adsorption rate of  $1.0 \times 10^{-4}$

575  $(s^{-1})$ , reflecting poor contact and very slow adsorption kinetics, probably due to its relatively short

576 chain length. By contrast, PFOA exhibited a little higher adsorption capacity of 51.1 mg/g and a

577 faster adsorption rate constant of  $1.4 \times 10^{-1}(s^{-1})$ . The highest adsorption capacity was shown for

578 PFNA as 215.9 mg/g, which strongly indicates a preference towards long-chain PFAS compounds.

579 It thus appears from these results that PFAS chain length influences the adsorption kinetics-

580 adsorption capacity, with longer chains enhancing the capacity and medium chains increasing the

581 speed.

582 Though Ti<sub>3</sub>C<sub>2</sub> MXene showed higher removal efficiency (>80%). its practical usability on

583 a large scale is still limited by the expensive synthesis process and the involvement of toxic

584 chemicals (such as hydrofluoric acid (HF)). Further studies are required to evaluate its stability

585 and usability.

586

### 587 4.3 2D Metal-Organic Frameworks

588 Many types of 3D MOF have been applied in the removal of PFAS, such as NU-1000 (Li et

589 al. 2021), Cr-MILL-101 (Barpaga et al. 2019), UiO-66 (Hua et al. 2024), and MIL-53-AI-BPDC

590 (Zhao et al. 2021). The details of their high performance could be found in other studies as this

591 work focuses on the 2D form of MOFs.

592 In a study by Chen et al (Chen et al. 2016), examined the effectiveness of various MOFs

593 such as ZIF-7, ZIF-8, and ZIF-L(2D MOF) for PFOA decontamination from water. It underlined

594 the profound effect of interior surface chemistry and crystal structure on the adsorption

performance. Among other adsorbents, ZIF-L had the highest adsorption capacity for PFAS of about 1.2 mmol/g. Compared to ZIF-8, the adsorption of PFOA by ZIF-L was greater in the high concentration region. Its adsorption in the low concentration region was over two - fold higher than that of ZIF-8. Adsorption was highest at pH=5, though because of its low acid stability, the performance was poorer at pH=3. This was mainly because it is of layered structure, which ensures improved interlayer spaces and allows molecular transfer. In the case of ZIF-L, the possibility of PFAS molecules to pass between layers is better due to its lamellar structure and hence greatly enhances the adsorption efficiency.

#### 4.4 Covalent Organic Frameworks

The organized network of COFs allows for functional group alignment that strengthens the interactions between COFs and PFAS. Performance of adsorption can be improved through four general approaches: manipulating functional groups to increase electrostatic attraction; adding fluoro functional moieties to improve the effects of fluorine; increasing the effects of hydrophobic interactions; and adjusting the surface area and pore sizes for selective uptake of PFAS substances (Li et al. 2023).

Researchers introduced a new viologen-based covalent organic framework (VZ-COF) that removes PFAS from water. VZ-COF contains hydrogen-bond acceptors, positively charged functional groups, and hydrophobic regions for the attachment of PFAS, as demonstrated in Figure 14. The morphology of VZ-COF was characterized by SEM and HRTEM, confirming its well-defined morphology and crystalline structure.

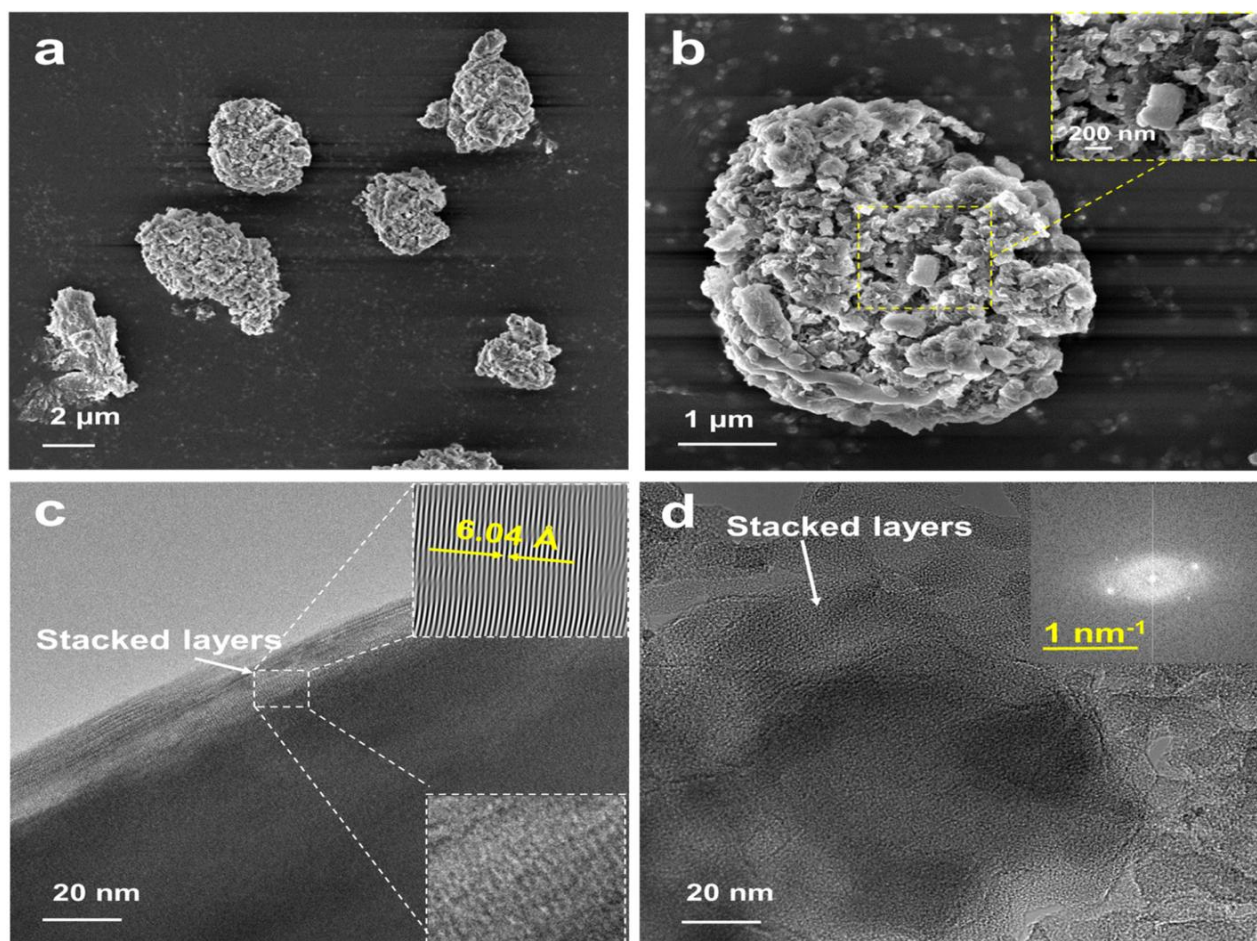


**Figure 14.** (a and b) SEM images of VZ-COF. (c and d) HRTEM images of VZ-COF, and the top inset in (d) shows the FFT of the highlighted region (Zarei et al. 2025).

Its construction involved a newly synthesized aromatic tetraamine linker, Quaternary Phenyl Poly-Tetra Amine (QPPTA), in conjunction with a Zincke salt. The COF exhibited an increased PFAS binding capacity by incorporating elements that allow different modes of interaction. The COF exhibited PFOA removal rates of nearly 99.6% at detection sensitivities down to  $0.1 \mu\text{g/L}^{-1}$ . The mechanisms and characteristics that explain VZ-COF's PFAS adsorption capacity will be explored. Electrostatic and hydrophobic interactions between the PFAS and the adsorbent are the main mechanisms inducing PFAS adsorption; however, the surface area, charge, porosity, shape, and particle size of the sorbents have also surprisingly influenced the affinity and capacity of solids adsorbents for PFAS molecules. The zeta potential of +28.1 mV, due to the viologen units, supports electrostatic interactions as VZ-COF's mechanism for PFAS removal. During practical evaluations, VZ-COF effectively lowered PFOA and PFOS levels from  $1.0 \mu\text{g/L}^{-1}$

<sup>1</sup> to less than 4.0 µg/L<sup>-1</sup>, far below the U.S. EPA's recommended limits. Its strong performance in both real tap water and synthetic wastewater, along with fast adsorption kinetics, substantial adsorption capacity, and the ability to be reused, highlights its promising potential for real-world PFAS remediation (Zarei et al. 2025). Table 5 shows selected studies that used the COFs to remove PFAS.

**Table 5.** Some recent studies that used COFs to remove PFAS.

| Absorbent Material             | Type of PFAS   | Capacity (mg/g)                | Concentration (mg/L)             | pH                           | Time (h)   | Removal Efficiency (%)                            | Reference           |
|--------------------------------|----------------|--------------------------------|----------------------------------|------------------------------|------------|---------------------------------------------------|---------------------|
| VZ-COF                         | PFOS           | 1000 mg L <sup>-1</sup>        | 1.0                              | 7                            | 0.75       | >99                                               | (Zarei et al. 2025) |
| 28%[NH <sub>2</sub> ]-COF      | Gen X          | 200                            | 0.2-100                          | -----                        | 0.5        | >90                                               | (Ji et al. 2018)    |
| BT-BDB-COF (COF <sub>2</sub> ) | Gen X, HFPO-TA | 679.8 (GenX), 1071.4 (HFPO-TA) | 0.05–0.6 mmol/L (50 mL) /50 mg/L | 7                            | 6-12       | 80 - 100                                          | (Wang et al. 2021)  |
| chitosan/F-COF                 | PFOS           | 8745.6                         | 0.05                             |                              | 0.016–24   | Fast initial removal, equilibrium at 4 h          | (He et al. 2022)    |
| TG-PDCOF                       | PFOA           | 2600                           | 0.2                              | Decreased with PFOA increase | 0.5 and 22 | 96 in seconds (high conc.), 83 in 1 h (low conc.) | (Jrad et al. 2024)  |
| COF2                           | GenX           | 2.16 mmol/g for                | 0.0756 mmol/L                    | 7                            | 12         | >99.9                                             | (Wang et al. 2021)  |

VZ-COF demonstrated excellent removal efficiency and successful application in real tap water and simulated wastewater samples. Rapid kinetic adsorption, high capacity, and ease of reusability confirm its practical application for removing PFAS from polluted water sources. 28%[NH<sub>2</sub>]-COF attained removal efficiencies over 90% throughout a broad spectrum of concentrations (0.2–100 mg/L), indicating significant versatility. In contrast, BT-BDB-COF (COF<sub>2</sub>) was a high-capacity adsorbent for GenX and HFPO-TA (from 80% to 100% removal).

Nevertheless, it demands a long residence time of 6 to 12 h, potentially limiting its application in a continuous process, as well as the overall complexity of the formulation, leading to an increased cost of production. Chitosan/F-COF exhibits remarkable adsorption properties, with a strong capacity of 8745.6 mg/g, and achieves rapid equilibrium, indicating a strong potential for practical applications. However, the studies fail to evaluate how it operates under different pH or real wastewater conditions. Furthermore, the long-term effectiveness of the chitosan structure in a range of chemical environments is still undermined by the uncertainty of retaining its effectiveness. TG-PDCOF exhibited a rapid removal rate; however, its effectiveness decreased with an increase in PFOA concentration, presumably suggesting rapid saturation of the material which may limit its use more broadly. COF2 provided good efficiency at moderate concentration.

#### **4.5. Layered Double Hydroxides**

Previous studies have explored the potential of LDHs as effective materials for adsorbing anionic pollutants, including both long- and short-chain PFAS, from water contaminated with microbes. It also examined whether modified LDHs could degrade PFAS compounds. The authors analyzed how the structural differences in LDH types and the chemical complexity of PFAS influence removal mechanisms, as shown in Figure 15. TEM images of pristine ZVI particles (Figure 15a) and the ZVI/LDH composite (Figure 15b) illustrate the morphological changes resulting from composite formation. Furthermore, X-ray photoelectron spectroscopy (XPS) analysis, including the survey scan (Figure 15c) and the high-resolution scan of Fe 2p (Figure 15d), provides insight into the surface chemical states and confirms the successful integration of ZVI within the LDH matrix. LDHs show promise as preliminary treatment agents, removing pollutants through mechanisms such as ion exchange between layers, surface-level chemical reactions, and reactivation after calcination. Results highlighted notable differences between the two LDH types in their ability to remove PFOA. Specifically, MgAl-LDH removed about 16.2% of PFOA within the first five minutes, with no further removal afterwards, while MgFe-LDH continued to reduce PFOA levels throughout the entire reaction period. This variation indicates that the chemical makeup of LDHs plays a critical role in determining their adsorption efficiency by influencing how they interact with PFOA molecules on the surface (Yan et al. 2024).

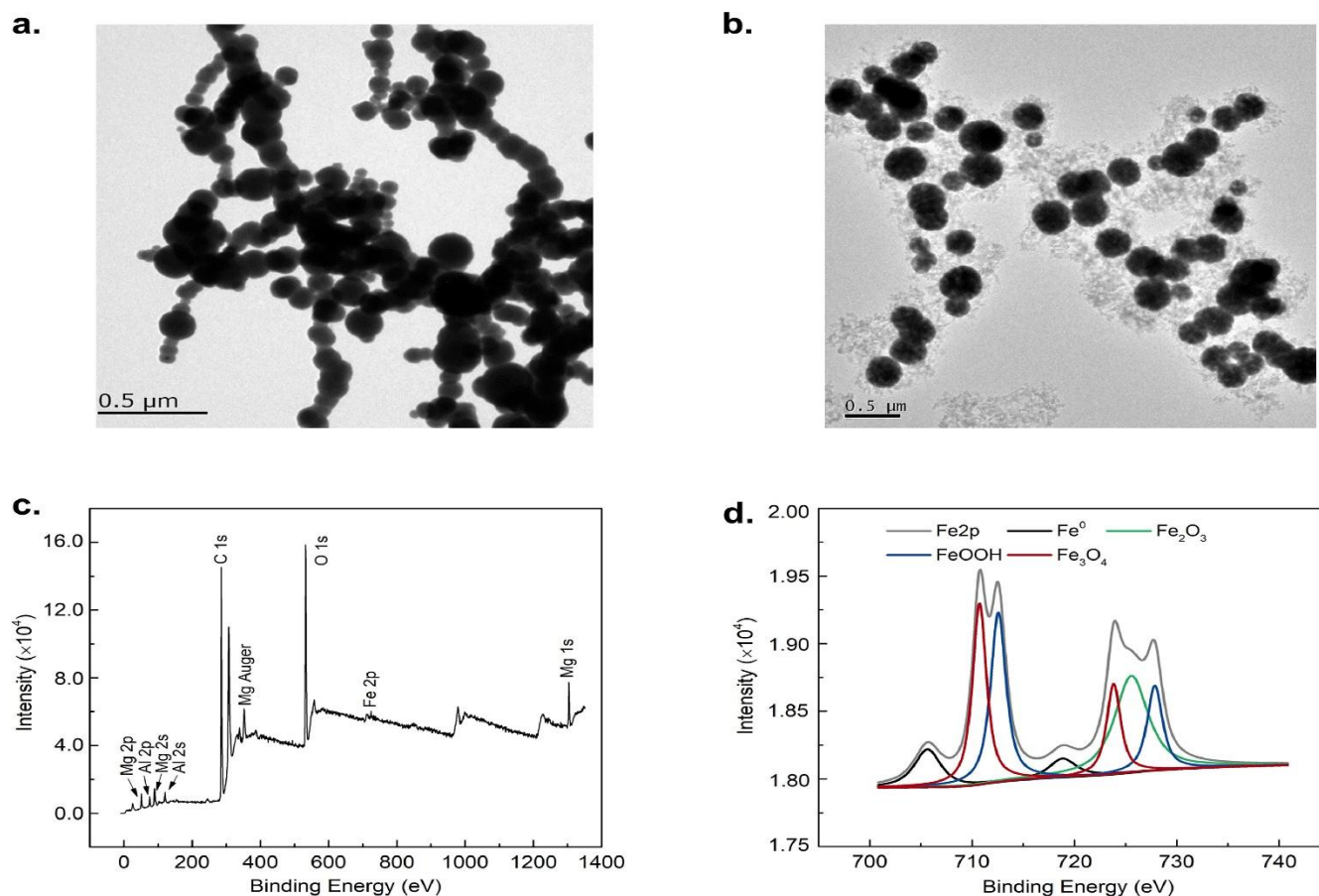


**Figure 15.** TEM images of pristine ZVI particles (a) and the ZVI/LDH composite (b); XPS analysis of the ZVI/LDH composite: survey scan (c) and narrow scan of Fe 2p (d) of the ZVI/LDH composite (Yan et al. 2024).

A different study looked at how PFAS-9 interacts with hydrotalcite (HT), which is a layered double hydroxide, when PFAS levels are low in the environment. It also looked at how the temperature of calcination and various ions in water affect adsorption, as well as how effectively the material can be reused following thermal regeneration. The results indicated that PFAS and PFOS adsorption attained equilibrium after four hours, but the trials were conducted for 24 hours to confirm complete equilibrium. The adsorption performance comparison of untreated and thermally treated adsorbents indicated the following ranking for PFOS affinity: MG63HT < c (200)  $\approx$  c (300) < c (600) < c (400)  $\approx$  c (500). The enhanced performance of c(400) was likely attributable to decarbonation, which increased the availability of active adsorption sites. For the aged c (400) material, the sequence of PFAS adsorption affinity was: PFBS < PFBA < PFOS < 6:2 FtS < PFHxS < PFOA < PFNA < N-EtFOSAA < PFOSA. The mechanism was the adsorption of negative ions

of pollutants within the positive layers of LDH by electrostatic and hydrophobic forces, which allows for their efficient removal from polluted water (Kim et al. 2024). Table 6 shows selected studies that used the LDHs to remove PFAS.

**Table 6.** Some recent studies that used LDHs to remove PFAS.

| Absorbent Material | Type of PFAS | Concentration (mg/L) | Capacity (mg/g)               | Sorbent Mass (g/L) | pH   | Time (h) | Removal Efficiency (%) | Reference            |
|--------------------|--------------|----------------------|-------------------------------|--------------------|------|----------|------------------------|----------------------|
| Zn–Al LDH          | PFOA         | 10                   | 625                           | 0.25               | 6    | 1-2      | >98                    | (Huo et al. 2022)    |
| LDH-CF             | PFOA         | 0.5                  | 1333                          | 1                  | 6-7  | 0.083    | >90                    | (Min et al. 2022)    |
| Mg–Al LDH          | PFOS         | 207.6-1038           | 0.10-1.0(PFS/A 1 molar ratio) | -----              | 9-10 | 1        | ~100 (low conc.)       | (Aisawa et al. 2018) |

The Zn–Al LDH also performed better in comparison to other sorbents for the PFOA removal at 10 mg/L under acidic conditions (pH 6), although this might restrict its application to naturally alkaline environments. While CF LDH showed a remarkable adsorption capacity, its performance was evaluated only at low contaminant concentrations, raising doubts about its performance when applied to highly contaminated industrial effluent. Mg–Al LDH, however, was more effective even at higher concentrations (up to 1038 mg/L), and all the dioxin was close to completely removed. However, the experiment mainly considered low concentrations for higher efficiency, and the adsorbent quantity was not mentioned.

#### 4.6. Phosphorene and Hexagonal Boron Nitride

Although there are few studies on the use of phosphorene in the adsorption of PFOA compounds, Laibao et al (Liu et al. 2020) employed density functional theory (DFT) to simulate the adsorption of PFOS on various phosphorene models. They studied four types of phosphorene, namely pristine, Stone-Wales (SW) defect, Single vacancy (SV) defect, and Double vacancy (DV) defect, evaluating the adsorption energy and electron density changes. The study revealed that pristine phosphorene had a modest adsorption energy of approximately -0.87 eV with PFOS. Introducing structural defects, including Stone-Wales transformations, single vacancies (SV), and double vacancies (DV), considerably enhanced adsorption. Specifically, SV and DV defects

increased the adsorption energy to -1.43 eV, largely due to greater electron localization and the development of more reactive adsorption sites. Adsorption occurred via chemisorption at the SV defect, where oxygen atoms in PFOS formed bonds with an unpaired phosphorus atom, as shown in Figure 16. Isosurface images of the electron density difference for PFOS adsorbed on the single vacancy-defected phosphorene with different strain rates (Yellow: electron accumulation; Blue: electron depletion).

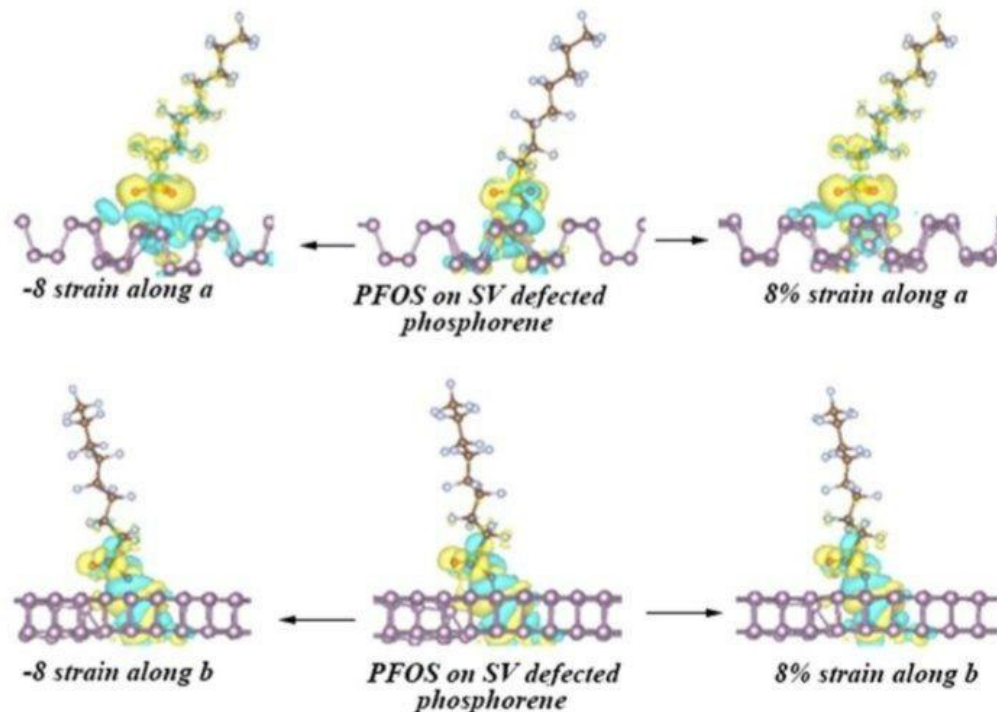


**Figure 16.** Isosurface images of the electron density difference for PFOS adsorbed on the single vacancy defected phosphorene with different strain rates (Yellow: electrons accumulation; Blue: electrons depletion) (Liu et al. 2020).

Researchers investigated (Feng et al. 2016) graphene-like hexagonal boron nitride nanosheets and evaluated their efficacy in eliminating PFOS and PFDA from water under various solution conditions. The morphological and structural characteristics of the prepared h-BNs are shown in Figure 17. The materials demonstrated significant adsorption efficiency, reaching equilibrium in under two hours for both pollutants. The sorption behavior was consistent with pseudo-second-order kinetics and aligned well with the Freundlich adsorption model. When using a solution containing 50 mg L<sup>-1</sup> PFAS, 0.2 g L<sup>-1</sup> h-BNs, and 5 mM ammonium acetate at pH 6.0, the sorption capacities were about 0.72 mg m<sup>-2</sup> for PFDA and 0.45 mg m<sup>-2</sup> for PFOS. The influence

of  $H^+$  and  $Ca^{2+}$  ions observed in the solution suggests that electrostatic forces primarily controlled the sorption processes. Calcined h-BNs exhibited consistent sorption efficacy, and the incorporation of  $Ca(OH)_2$  during the calcination process remarkably enhanced fluoride immobilization in the presence of BNs. The results indicate that h-BNs may function as an effective adsorbent for the elimination of PFASs from water. However, further investigation is necessary to evaluate their efficacy against a wider spectrum of PFAS chemicals.

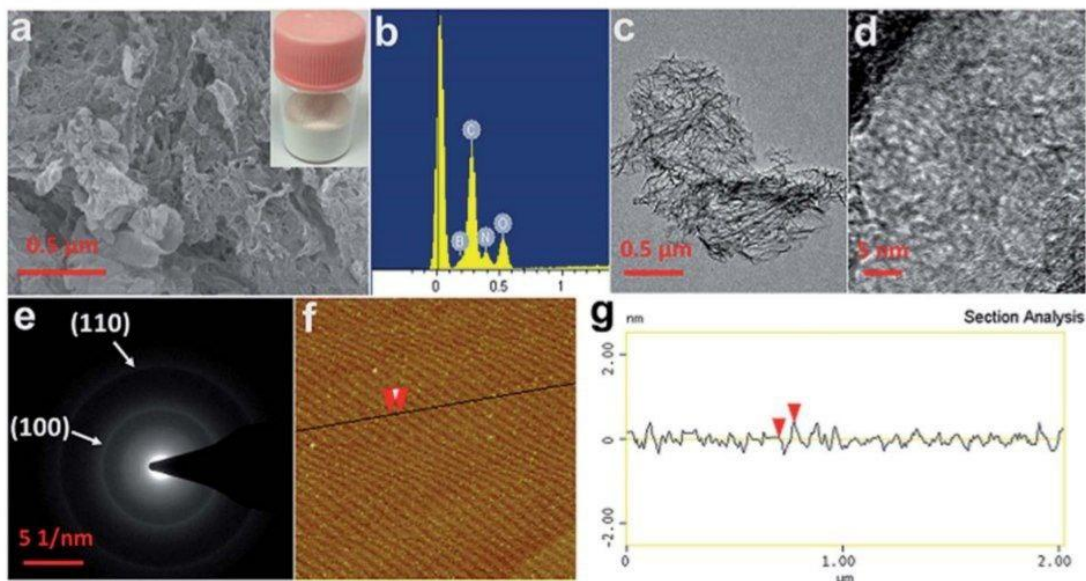


**Figure 17.** a) Scanning electron microscopy. (b) energy-dispersive X-ray spectroscopy, (c) transmission electron microscopy, (d) high-resolution transmission electron microscopy images, (e) diffraction rings of the prepared h-BNs. (f) atomic force microscopy image of h-BNs on mica, and (g) cross-section along the black line in (f). The image of h-BNs is shown in the inset in (a) (Feng et al. 2016).

## 5. Adsorption Mechanisms

Various remediation technologies have been applied for PFAS pollution abatement, which mainly include adsorption methods, membrane-based separation, chemical or electrochemical degradation, and biological remediation (Garg et al. 2023)(Blotevogel et al. 2023). The adsorption method has been regarded as a cost-effective and very efficient approach to rapidly remove PFAS from contaminated water (Smaili and Ng 2022). Conventional adsorbents include granular activated carbon, which is widely used in municipal and residential water treatment processes for the removal of PFAS. However, despite their use, they suffer from many shortcomings, including limited adsorption rate, poor selectivity, and reduced effectiveness toward short-chain or

hydrophilic PFAS (Yu et al. 2023)(Jiang et al. 2023)(Ilango et al. 2023). Granular activated carbon demonstrated markedly inferior adsorption of the short-chain PFBA (C4), exhibiting performance 5–10 times lower than that of the long-chain PFOA (C8) in both batch and column testing scenarios (Park et al. 2020).

Adsorption is an effective and extensively utilized technique for removing PFAS from polluted water (Abbasian Chaleshtari and Foudazi 2022)(Shrestha et al. 2021)(Du et al. 2014). PFAS adsorption is influenced by electrostatic, hydrogen bonding, and hydrophobic interactions (Abbasian Chaleshtari and Foudazi 2022), depending on the adsorbent, the nature of the adsorbates, and the solution chemistry (Militao et al. 2021)(Garg et al. 2021). Hydrophobic interactions arise from entropic effects. When PFAS molecules adsorb onto a hydrophobic sorbent, the previously structured water molecules surrounding the hydrophobic areas are released, hence augmenting the system's entropy (Cai et al. 2022)(Mohona et al. 2023). Additionally, strong hydrophobic interactions can lead to the formation of hemimicelles and micelles on the adsorbent surface, even at PFAS concentrations much lower than their critical micelle concentration (Westreich et al. 2018).

Graphene oxide also highly interacts with numerous pollutant molecules given the large surface area and the presence of functional groups as hydroxyl, carboxyl, and epoxide. Interactions with cationic compounds like cetyltrimethylammonium chloride lead to the formation of a surface positive charge, making it stronger than the electrostatic attraction to PFAS, which are negatively charged molecules. Morphological studies showed that CTAC modification reduces the particle size from  $2.75 \pm 0.81 \mu\text{m}$  (GO) to  $0.69 \pm 0.79 \mu\text{m}$  (GO-CTAC), which improves the dispersion and the accessibility of the active sites as well. The positive charge affinity graph set out CTACs ion-counter surface pores, obtaining near complete elimination of PFAS in an hour. When PFAS bonded with CTAC on modified graphene oxide, CTAC). There are many remarkable combinations of phenomena at work initially. The electrostatic forces structuralize at close proximity due to the surface charge generated as quaternary ammonium groups are shielded as an encapsulating mechanism and face the PFAS anionic radiating head. Subsequently, positive chain-goal PFAS agents move toward hydrophobic zones of the screens, strengthening the fixation of elongated PFAS. Eventually, the ion structure will be reversed with PFAS shackling to the quaternary ammonium groups and fluorinated chains, about gaining free anions with PFAS. The

theory defines the reality possessing an excited fluorinated level of electrostatic charge as C (Pervez et al. 2024).

Modification of the amino group of graphene oxide, followed by its incorporation with  $\text{Fe}_3\text{O}_4$  nanoparticles, creates proton-active sites for  $\text{NH}_3$  between acidic to neutral pH conditions to provide strong electrostatic attraction towards negatively charged PFAS. The hydrophobic basal planes of graphene oxide interact with the fluorocarbon chains of PFAS, increasing the adsorption process by hydrophobic forces. The inclusion of  $\text{Fe}_3\text{O}_4$  allows for an easy magnetic retrieval of the adsorbent while simultaneously increasing surface heterogeneity. The adsorption mechanism entails a synergistic dual mode: (1) electrostatic binding between protonated amine groups and negatively charged PFAS functional groups, predominant at  $\text{pH} \leq 7$ , and (2) hydrophobic interactions between graphene sheets and the fluorocarbon backbones of PFAS, which remain substantial even when electrostatic attraction diminishes at elevated pH levels. Zeta potential tests were performed to determine the charge characteristics of the adsorbent: graphene oxide was highly negatively surface charged (-33.9 mV), whereas the amine-modified,  $\text{Fe}_3\text{O}_4$ -loaded graphene oxide had a lower negative charge (-27.8 mV), confirming the presence of proton-active amine groups. At acidic pH, these amines are completely protonated, increasing surface cationicity and promoting PFAS adsorption. As pH increases, partial deprotonation diminishes the positive charge, decreasing electrostatic attraction; nonetheless, hydrophobic interactions continue to effectively promote adsorption (Mahpishanian et al. 2024). Modifying GO with alkyl amine chains adapts the chemistry of the inherently negatively charged GO surface and enhances its affinity for PFASs. The presence of N, N-dimethylethylenediamine chains on GO results in the presence of hydrophobic methylene groups and terminal amines that orient toward the aqueous phase. Adsorption primarily takes place by van der Waals forces and hydrophobic interactions between hydrophobic molecules of GO-modified and fluorocarbon chains of PFASs, and the electrostatic repulsion by negatively charged GO structure for the negatively charged carboxyl and sulfonate groups of PFASs. This effect is overcome by the strong hydrophobic bond. It is worth noting that when squaring the N, N-dimethylethylenediamine chains to produce positively charged ammonium sites, the adsorption capacity is not enhanced, indicating that electrostatic attraction plays a secondary role compared to van der Waals forces (Trifoglio et al. 2025).

Two-dimensional carbides or nitrides of transition metals (i.e., MXene) (Naguib et al. 2011), When using acid-etched titanium carbide MXene ( $\text{Ti}_3\text{C}_2\text{Tx}$ ), it is used in combination with

PEDOT:PSS. This combination constitutes an organic-inorganic hybrid system that enhances adsorption properties. Acidic etching expands the specific surface area, pore volume, and pore size, while the PEDOT component retains the interlayer spacing of MXene for accessibility to the intercalation of ions so that the MXene layers do not restack. All these structural changes help yield four times the volumetric capacity of an untreated MXene, which is key to electrosorption efficiency. The adsorption mechanism is largely electrostatic in nature. When a positive voltage is applied, deprotonated PFAS molecules (that are anions due to either their carboxylic or sulfonate terminal groups) are substantially attracted to the electrode surface, which is positively charged. The MXene is composed of layers that permit the anionic PFAS to intercalate between and into the layers. The PEDOT component provides conductive chains that are able to provide charges for efficacy and stability. When the voltage is flipped to a negative voltage, the electrostatic attraction is eliminated, and the PFAS that were adsorbed into the MXene interlayers will be released back into the solution. Importantly, a reversible adsorption-desorption cycle occurs.

The adsorption mechanism of 2D MOFs such as ZIF-L differs from that of 3D MOFs such as ZIF-8. The 2D MOFs are less geometrically spaced, which makes them less diffusion-resistant and allows PFOA molecules to quickly migrate to ZIF-L. Since ZIF-L is composed of 2-methylimidazole bonds, which are positively polarized regions, and deprotonated PFOA is negatively charged, adsorption occurs through electrostatic attraction. The hydrophobic core structure of PFOA and the nonpolar surface domains of ZIF-L enhance stability through hydrophobic interactions (Chen et al. 2016).

The viologen units in the VZ-COF backbone exhibit a positive surface charge, generating a strong electrostatic attraction with the anionic PFAS molecules. The fluorinated chains (which act as hydrogen bond acceptors) in PFAS and the aromatic regions of the COF form hydrophobic interactions. In addition, hydrogen bonds exist between the PFAS groups and the nitrogen-containing sites (Zarei et al. 2025).

Although pure LDHs have positively charged layers that generate strong electrostatic interactions with PFOA, LDHs are naturally hydrophilic, which limits the occurrence of hydrophobic interactions. Researchers functionalized their surfaces using alkyl groups (-CH) and polyfluoroalkyl groups (-CF), increasing the hydrophobicity of the material while maintaining its positive charge. This dual mechanism of electrostatic and hydrophobic interactions results in faster kinetics and a higher adsorption capacity. Zeta potential measurements revealed that LDHs form

complexes with PFOA on the inner shell, and a significant shift in the zero-charge point was observed after adsorption, where the charge drops remarkably (Min et al. 2022).

Phosphorene is the 2D monolayer of black phosphorus. Phosphorene is a good PFOS adsorbent because of its remarkable black phosphorus surface adsorbent properties and electronegativity. Its high surface reactivity, tunable bandgap, and anisotropic framework allow easy interaction with polar and fluorinated impurities. PFOS adsorption on phosphorene is mainly explained by charge transfer and chemical bonding between the PFOS sulfonate group ( $-\text{SO}_3^-$ ) oxygen atoms and sulfonate phosphorus atoms on the phosphorene surface. In Density Functional Theory (DFT), the SV defect is said to add a chemically active phosphorus atom that will form a bi-directional P-O bond (about 1.7 Å) with the PFOS molecule, and that is true with all of the defected structures, SW, SV, and DV. The chemical bond explains the high adsorption energy ( $E_{\text{adb}} = -3.17$  eV) as opposed to pure phosphorene -2.19 eV. Bader charge analysis shows that phosphorene at SV locations transfers about 0.78  $e^-$  to PFOS which means that bond formation will have strong covalent character. The application of tensile strain in the a-direction increases adsorption by exposing active sites and modifying the band structure, while compressive strain increases adsorption as well (Liu et al. 2020).

Porous hexagonal boron nitride exhibits a high specific surface area of approximately 125.5  $\text{m}^2/\text{g}$ , good thermal and chemical stability, and a large pore volume. During the adsorption of PFOS and PFDA, the negative surface of h-BN interacts primarily through electrostatic forces. Both of these contaminants exist in deprotonated anionic forms at  $\text{pH} > 4$ , which causes electrostatic repulsion with the h-BN surface. Adsorption is enhanced, and the electrostatic repulsion is reduced, by the neutralization of the surface charge due to the presence of specific cations, such as  $\text{Ca}^{2+}$  and  $\text{H}^+$ . Hydrophobic interactions occur between the fluorocarbon chains and the BN surface. The adsorption was a heterogeneous multilayer, and the equilibrium data conformed to the Freundlich equation. The adsorption process followed pseudo-second-order kinetics, indicating that chemisorption was dominant (Feng et al. 2016).

## **6. Perspectives and challenges**

The ability of GO to adsorb anionic PFAS is hindered by its hydrophilic properties and negatively charged surface. Therefore, modifying the structure of GO is crucial to improving its adsorption efficiency. The researchers emphasized that GO modified with CTAC shows promise as a quick and effective material for removing PFAS from different water sources (Pervez et al.

2024). In addition, the removal effectiveness may be affected by the pH of the solution. Dayong et al. (Dayong et al. 2021) studied that AGO effectiveness decreased significantly with increasing pH of the system. The study used a PFOA concentration of 1000 mg/g. The improved performance has been demonstrated, resulting in reduced electrostatic repulsion, which increases the effectiveness of AGO. The study was confirmed by Mahpishanian et al. (Mahpishanian et al. 2024); GO alone is notably ineffective at adsorbing PFAS, particularly the short-chain form PFBS. This limitation arises from the negatively charged surface of GO nanosheets, attributed to their oxygen-rich functional groups, which repel the negatively charged PFAS compounds (PFOS, PFOA, PFHxS, and PFBS) in aqueous environments. While some adsorption does occur by electrostatic attraction at neutral pH (approximately 7), PFAS adsorption continues to take place at higher pH values, which indicates other forces are involved, including hydrophobic interactions. The determination of regenerability of MAGO adsorbent is necessary to keep up the efficiency in the removal of PFAS.

The aggregation or restacking propensity of adjacent MXenes flakes hinders the electrochemical efficiency of MXenes-based electrodes in practical applications (Liu et al. 2022). In response to these issues, poly (3,4-ethylene dioxythiophene) polystyrenesulfonate presents a viable option owing to its hydrophilic active and charge groups (Shrestha et al. 2024). In a study on the use of MOFs in the adsorption of PFAS (Liang et al. 2024). One of the challenges faced was that PCN-1002 had exceptional selectivity for PFOA while showing limited adsorption towards other PFASs such as PFBS, PFDA and PFSEA. In another study (Chen et al. 2016). Though ZIF\_L was very efficient in removing PFOA compounds, the results showed that the acidic stability of ZIF\_L needs to be improved for the continuous processes of PFOA sorption.

In another study (Aisawa et al. 2018), PFOS and PFOA ions were efficiently removed at low concentrations ( $1\text{--}5\text{ mmol}\cdot\text{dm}^{-3}$ ), predominantly via incorporation into LDH structures. At concentrations of  $10\text{--}20\text{ mmol}\cdot\text{dm}^{-3}$ , PFOS removal transpired through a dual mechanism of LDH creation and precipitation as a marginally soluble sodium salt, while PFOA was exclusively eliminated by LDH formation. Optimal conditions for PFOS removal were a Mg/Al molar ratio of 2, a PFS/Al molar ratio ranging from 0.10 to 1.0, a pH level of 9–10, and a temperature interval of 25–40 °C. According to Liu et al. (Liu et al. 2020), introducing single vacancy (SV) defects along with tensile strain can greatly improve phosphorene's ability to adsorb PFOS. The effectiveness of

this enhancement depends on the direction of the strain, with strain applied along the a-axis having a stronger impact than along the b-axis. Specifically, the combination of an SV defect and 8% tensile strain can increase PFOS adsorption to about 60%. However, this effect varies depending on the type and orientation of the defect; tensile strain may either boost or hinder the material's adsorption performance.

In a study on the use of porous hexagonal BN nanosheets (Feng et al. 2016), the relatively higher PFDA sorption capacity suggests that it is adsorbed more rapidly than PFOS. PFOS generally demonstrates greater sorption on sorbents than PFOA, due to its sulfonate group and longer perfluorinated carbon chain. Although most 2D materials have been combined with specialized functional groups (e.g., amino groups) to improve PFAS adsorption, the problem of competition with other contaminants (e.g., ions and organics) reduces performance efficiency. Field studies should be conducted on water containing a mixture of contaminants to verify the performance in the real world, not just in the laboratory. Molecular modeling (such as DFT and MD) should be used to understand exactly how the interactions occur and then design effective and improved materials physically and chemically.

## **7. Conclusions**

The present review summarizes six types of 2D materials, namely, Graphene, MXenes, MOFs, COFs, LDHs, Phosphorene, and h-BN, as advanced adsorbents for treating water contaminated with PFAS compounds in aquatic environments. These materials showed promising adsorption performance due to their high surface area, surface modification capabilities, and distinctive structural properties. The modified graphene showed high efficiency in removing PFAS, with amine-modified graphene oxide (AGO) reaching a removal capacity of 1575 mg/g of PFOA. The adsorption process followed the second-order kinetic model and the Freundlich adsorption model (Dayong et al. 2021). In comparison to conventional resins, which have removal efficiencies ranging from 70 to 80%, MXenes have shown much higher removal efficiencies. The reason it is effective in removing PFAS is the presence of electrocatalytic properties responsible for the strong molecular retention. It has been shown that the employment of MXenes with specific chemical groups increases the adsorption capacity and electrostatic interactions, thus improving their adsorption capacity for removal. It has been shown that advanced COFs designs integrate

hydrophobic domains for PFAS tail capture, positively charged sites for head group binding, and functional groups to enhance affinity. Most COFs have shown high efficiency in terms of the speed of reaching equilibrium time and reuse without any significant loss in performance. However, despite the success of removal, performance is weakened in terms of efficiency when organic materials or competing ions are present, and the adsorption capabilities of short-chain PFAS compounds are still limited. It has been shown that advanced COF designs integrate hydrophobic domains for PFAS tail capture, positively charged sites for head group binding, and functional groups to enhance affinity. Most COFs have shown high efficiency in terms of the speed of reaching equilibrium time and reuse without any significant loss in performance. However, despite the success of removal, performance is weakened in terms of efficiency when organic materials or competing ions are present, and the adsorption capabilities of short-chain PFAS compounds are still limited. Future research should focus on these challenges, as well as on other binary materials such as silicene, germanene, stanene, boronene, antimonene, tellurene, and others. Optimizing 2D materials represents a promising path toward effective, sustainable, and broadly applicable solutions for removing PFAS compounds in water treatment systems.

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## **Conflict of Interest**

There is no known conflict associated with this work.

## **Authors' Contribution**

T.M.A.: Writing original draft and drawing figures.

M.B.H.: Data collection and literature review.

M.J.J.: Methodology and validation.

A.J.H.: Visualization and editing.

S.S.: Writing, review and editing.

Z.H.A.: Revision, editing, and data curation.

M.F.T.: Revision and editing.

M.K.: Revision, editing, conceptualization, supervision, and project administration.

1568

1569 **Ethical Approval**

1570       This article does not contain any studies with human participants or animals performed by  
1571 any of the authors.

1572

1573 **Consent to Participate**

1574       Not applicable.

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1576 **Consent to Publish**

1577       All authors have read and approved the final manuscript and consent to its publication.

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1579 **Data Availability Statement**

1580       Any needed data will be available on request.