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Recent Advances in PFAS Removal from Water: A Mini Review of Treatment Strategies

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Abstract

Per- and polyfluoroalkyl substances (PFAS) are forever chemicals with strong, unbreakable C-F bonds, posing a serious environmental and global health concern. The Environmental protection agency has regulated and implemented the strict permissible levels of PFAS in water matrices to prevent it from causing further damage. The source, occurrence and toxicity of PFAS was briefly reported to understand the need for its removal and degradation from water sources. Various removal strategies are adopted for the removal and degradation of PFAS among which the mini review focuses on the advanced methods like adsorption, membrane filtration, and Advanced Oxidation Process (AOP) and providing an insight into the methods' innovative approach to remove and degrade PFAS by incorporating different mechanisms. The innovative adsorbents like biochar, metal organic frameworks and conventional granular activated carbon removal efficiency and its limitation for short chain compounds were also emphasized. In case of membrane filtration, parameters increasing or impacting the rejection efficiency were reported. Destructive processes like AOP efficiency in defluorination of PFAS was discussed. The review also emphasises the need for the development of hybrid methods that could effectively degrade both long and short chain PFAS. Future scope and research direction insist on the development of methods that are scalable and cost-effective methods for PFAS and mitigating PFAS to achieve complete elimination.

Keywords: Forever chemicals, Per- and polyfluoroalkyl substances (PFAS), water treatment, Adsorption, Membrane filtration, Advanced Oxidation process

Introduction

Per- and polyfluoroalkyl substances (PFAS) are man-made organic compounds that contain fluorine and have unique physical and chemical properties because of the strong carbon and fluorine bonding (C-F). PFAS are made up of carbon chains and the hydrogen can either be completely or partially replaced with fluorine atoms. Due to presence of more fluorine atoms PFAS has become more hydrophobic and lipophobic although there is the presence of functional groups like sulfonic and carboxylic groups. They don't break down; they are commonly referred to as "forever chemicals." There are more than 5,000 distinct kinds of PFAS globally (1). PFAS that are hydrophobic and oleophobic, PFAS are classified into two main categories: long-chain and short-chain. Long chain has C9-C14 carbon atoms, and short chain has C4-C6 carbon atoms. PFOA, PFOS are most commonly used in various industries. Due to regulations and bans in the use of PFOA and PFOS the long chain is replaced with a short chain that possesses similar properties. PFAS are utilised a lot in many industries because they are very resistant to heat, oil, and water. For example, they are used as surfactant intermediates like firefighting foams, hydraulic fluid for aircrafts, waterproofing treatment for apparels and carpet, coating of household cooking products. The PFAS contamination in the water are mainly due to firefighting activities, fluorochemical discharge from industries and degradation from the products used by the

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consumers. PFAS bioaccumulation and magnification in the organisms increase with increasing chain length (2). The PFAS occurrence in various water matrices are due to the various anthropogenic activities. PFAS exhibits toxicity in various levels causing serious damage to aquatic organisms and humans. Ecotoxicological studies on PFAS reported thyroid disorders, fluctuation in the hormonal levels, creation of more oxidative stress, negative effects in the hatching rate, development of embryos and motor function. The studies with low concentrations of PFAS also showed a decreased egg diameter and sperm density. The toxicological studies on humans with PFAS accumulation reported cancer affecting organs like kidney, liver, and breast. Cardiovascular-related ailments and hypertension, PFAS are also endocrine disruptors, causing thyroid and sex hormones malfunction. PFAS accumulation showed serious effects in brain disorders like Alzheimer's, stroke, cerebral palsy, Parkinson's, short-term memory, hearing loss and reduction in the brain structure volume (3).The increasing awareness of the PFAS contamination led to setting various regulations for PFAS in water, aiming to protect the water sources and human health with permissible limits for forever chemicals. Table 1 provides detailed information on the standards set by the United States Environmental Protection Agency (USEPA). Different removal strategies are adopted for the removal of PFAS from water. Various conventional methods could not remove PFAS due to their persistent and unbreakable nature and also the PFAS concentration in the effluents are higher due to the precursor compounds that transform into stable PFAS compounds during treatment process increasing the concentration unintentionally (4). Due to their toxicity, persistence and occurrence PFAS elimination has emerged as the major challenge in water treatment. PFAS remediation methods involve separation methods and destructive methods this mini review aims to report the various advanced methods like adsorption, membrane filtration and Advanced Oxidation Process (AOP) its removal mechanism, rejection and removal efficiency for both short and long chain PFAS (4). The review also summarizes the current challenges and future outlook and research direction for the PFAS removal from water matrices.

Source and Occurrence of PFAS

PFAS contamination in water originates from various sources, all of which are anthropogenic. PFAS has wide range of industrial and consumer items since 1970, which includes carpets, leather treatments, coatings for cooking and kitchenware, outdoor apparel, mist suppressants for metal plating, and is extensively used in firefighting foams. The extensive application of these compounds arises from several advantageous qualities, such as water repellence when developed into fabric, non-stick surfaces via water and lipid repellence when coated on kitchen ware, and resistance to stains, heat, and chemical resistance (5). Owing to the sturdy C-F bonds in PFASs, they exhibit significant stability and are unlikely to break down readily in environmental matrices. PFAS in the environment have resulted from several

Table 1: Permissible limits set by the United States Environmental Protection Agency (US EPA)

S. No	PFAS Compound	Permissible limit
1	PFOA - Perfluorooctanoic acid	0
2	PFOS - Perfluorooctane sulfonic acid	0
3	PFNA - Perfluorononanoic acid	10 ppt
4	PFHxS - Perfluorohexane sulfonic acid	10 ppt
5	GENX - Hexafluoropropylene oxide dimer acid	10 ppt
6	Mixtures of PFHxS, PFNA, HFPO-DA, and PFBS	1 (unitless Hazard index)

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sources. The origins of PFAS in groundwater, drinking water, and surface water can be classified into point and diffuse sources. Point source is a specific discharge site, and the diffuse source contributes to PFAS contamination in water (Fig. 1). The most common sources are wastewater treatment plants (WWTPs), Landfill leachate, industrial sources, urban runoff, and fire-fighting foams specifically aqueous film forming foams (AFFF) (6). Wastewater treatment plants are considered the point source for PFAS. WWTPs don't have the ability to eliminate PFAS due to their persistent nature. The wastewater influents carry PFAS that are very concentrated. The various degradation treatment methods, also as biosolid removal, effluent discharge, and precursor degradation, also increase the concentration of PFAS, intensifying the contamination (7). PFAS exhibit exceptional surfactant ability, and hence they have been used in firefighting foams since 1960, and their usage in different countries for firefighting, training areas led to the exposure of PFAS contamination in water (8). municipal solid wastes around 140-150 million ton are dumped into the landfills PFAS present in the landfills and it can leach from contaminated soils due to infiltration, precipitation higher moisture content also increase the PFAS mobility into soil and as the time passes the leachate infiltrate deeper entering groundwater causing contamination in water (9). Another important source of PFAS contamination is the urban runoff the rainwater contacting PFAS-contaminated zones like industries carries high PFAS load to water sources like rivers and lakes. PFAS, due to their solubility, can remain in water and affect aquatic ecosystems. If the water from the contaminated zones is used by the people, it leads to various health issues and risks. Industrial areas are the main contributors of the urban runoff source of PFAS (10). Due to their persistence and mobility PFAS contamination sources have to be monitored to prevent further environmental loading and reduce their contamination in water. Various reports have been published on the occurrence, fate, and distribution of PFAS. The persistent nature of PFAS due its high solubility is the major reason for its

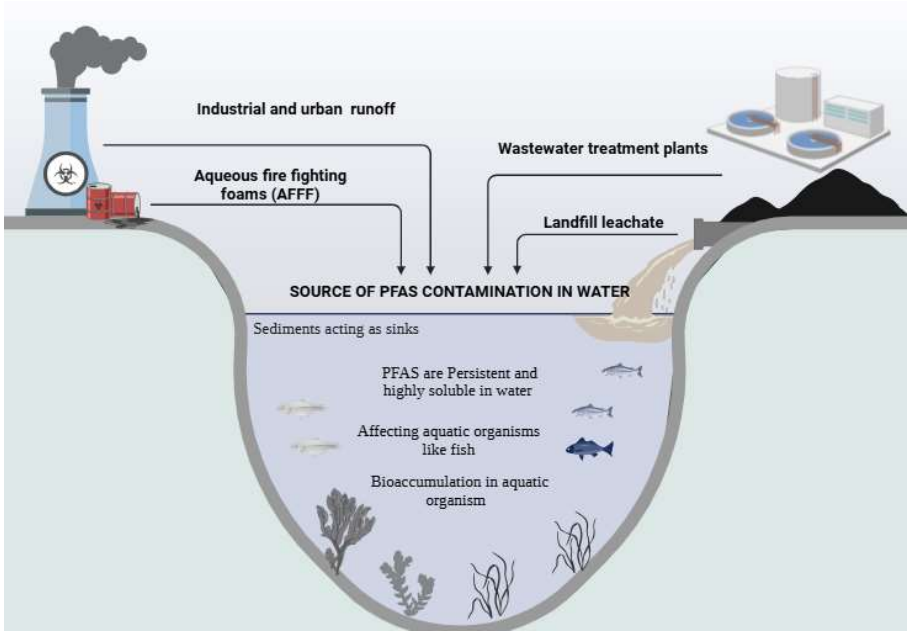

Fig 1: Source of PFAS contamination in water

PFAS Removal from Water

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contamination in ground, surface and ocean water and acting as sinks for the compounds and affecting multiple levels in the environment (11). Study conducted by Hariharan et al 2023 in the two different coastal systems of Bay of Bengal India. The regions focused were Digha-Sankarpur along the northeast coast in the Bay of Bengal and the Chennai coastal stretch from the southeast coast of Tamil Nadu. Two major PFAS compounds PFOA and PFOS spatial distribution was studied. In surface water, the PFOA concentration was found in the range <1.5-24.8 ng/L and PFOS in <1.6-13.9 ng/L and the sediment concentration were <1.7–7.7 ng/g and <1.5 to 5.5 ng/g for PFOA and PFOS. High concentration occurrence was is Adyar river mouth due to various industrial activities. Along the west Bengal cost highest PFAS levels were found in the Haldia and Hooghly River with PFOA in the range 14.0 ng/L and PFOS 9.0 ng/L in water 8.2 ng/g PFOA and 6.8 ng/g PFOS in sediment. Subarnarekha River showed occurrence with 12 ng/L PFOA in water. Among the rivers studied Haldia and Subarnarekha were heavily impacted by by the various industries, indicating the river samples showed higher PFAS concentration compared to the coastal area (12). PFAS occurrence in China surface water increased over a decade, and rivers like the Xiaoqing River had the highest occurrence with 1.06×10^6 ng/L followed by the Daling River with 2.31×10^3 ng/L concentration. Guanlan River also showed sixfold increase in the PFAS levels. The major contributors to the PFAS contamination are plastic, firefighting, and metallurgical manufacturing units. Seasonal variation also caused the PFAS levels in the rivers to fluctuate. The PFAS in Tibetan Plateau (TP) surface waters including rivers and glacial water were comparatively low from other region in the range 0.115–6.34 ng/L. Upstream, midstream and downstream showed occurrence with concentration 2 ng/L, 1.12 ng/L and 1.8 ng/L. PFBA and PFOS were the major pollutants in the glacial runoff with 61%. Seasonal transports form southeast and south Asia were the significant source of PFAS. Precipitation of PFAS was the major reason for the transport and occurrence of PFAS in TP (13). The occurrence of PFAS in Florida and northern region of united states of America showed was also studied. The PFOS and PFBS were more dominant and concentrations were close to parts per million in drinking water in the range 43-380 ppt for different PFAS. The ground water near fire training sites showed PFOS 47,000 ppt (6). Overall global monitoring of PFAS showed a widespread occurrence in ground, surface waters. The persistence and mobility nature of PFAS are the major reason for their transboundary concern. This finding implies on the importance of strict mitigation and monitoring of PFAS in water matrices to prevent further impact on health and ecosystem.

Toxicity of PFAS and its health impacts on humans

PFAS belong to man-made chemical and are hazardous and it has the capability to bioaccumulate in humans and cause serious health issues. The exposure of PFAS to humans has different routes like drinking water, soil and vegetation, occupational exposure, exposed through consumer products, indoor air and dust. Ground water, aquatic environment and fresh water are also contaminated due to various industrial activities that cause serious health implication to human and aquatic organisms. In case of soil and vegetation contamination in the soil matrix by contaminated ground water enter the plants by the uptake and enter the food chain and plants that are consumed by humans. Occupational exposure account for the exposure of PFAS to human that work in certain profession like fluorochemical plant workers, fire fighters, ski waxers, e-waste collectors leading to ingestion, inhalation and skin absorption. Various household items also are made from the precursor materials leading to exposure of PFAS in indoors, air and dust (14). Various studies were conducted to understand the toxic effects

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caused by PFAS in humans (Fig. 2). Kung et al 2021 conducted study on the cord blood plasma and serum of 165 children collected from the Taiwan Birth Panel Study (TBPS). The samples were collected from the children when they were eight years old, and mean concentration of PFAS in the samples was tested. The concentration of PFOA, PFOS, PFNA, and PFUA in cord blood of the children were 2.4, 6.4, 6.0, and 15.4 ng/mL and the concentration in the serum was 2.7, 5.9, 0.6, and 0.3 ng/mL. the prenatal exposure of PFOS in children reduced the lung function which was indicated with lower FEV1 (forced expiratory volume in 1 second) and lower PEF (peak expiratory flow). The effects were more predominant in children that were underweight (≤3200 g) during birth suggesting a prenatal exposure during critical lung development stages. It also indicated the disruption in the glucocorticoids, which are important in the maturation of lungs, which could lead to decreased breathing capacity, increased susceptibility to allergic respiratory conditions like asthma (15). Studies on PFAS associated with cardio vascular diseases data from the United States health project showed that the continuous exposure to contaminated PFAS drinking water increased the risk of high cholesterol, hypertension and coronary artery diseases. PFAS also was noted to interfere with the lipid metabolism leading to atherosclerosis. Long term exposure may increase the risk of stroke and heart failure (16). PFAS is also endocrine disruptors it impairs the reproductive health by increasing oxidative stress, interfering in steroid hormone production, causing damage to Leydig and Sertoli cells in males and polycystic ovarian syndrome, oxidative stress in granulosa cells and decreased endometrial receptivity causing hormonal disruption, altered cell signalling in both male and female fertility and reproductive function(17).

Different Removal strategies for PFAS

PFAS can be removed from water using different removal strategies. Most

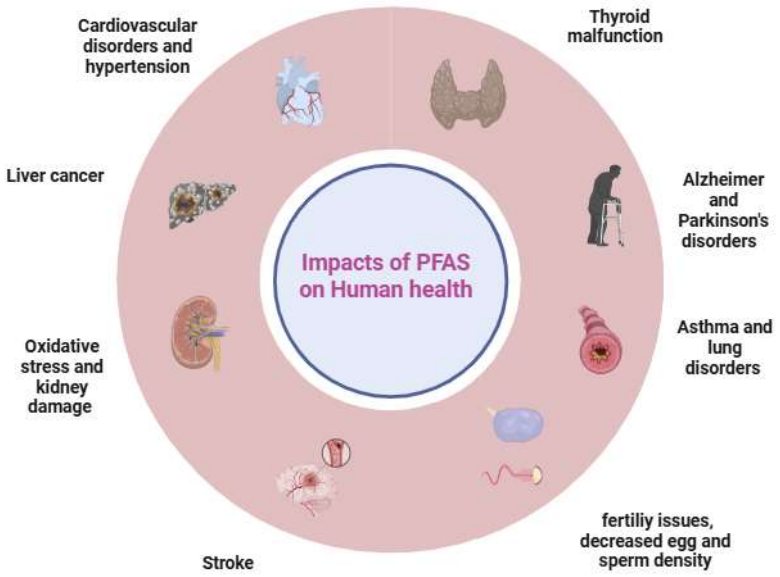

Fig 2: Impacts of PFAS on Human Health

PFAS Removal from Water

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commonly adopted methods involve the separation of PFAS and the degradation of PFAS from water. The separation methods involve adsorption (18), flocculation, coagulation (19), sedimentation (20), and filtration (21). The degradation of PFAS methods includes an advanced oxidation process (22), ultrasonication (23) and biological removal using microorganisms(24). Each of these methods has its benefits and limitations, and works differently. They are various limitations in conventional methods. For instance, during flocculation and coagulation, PFAS don't bind to the coagulants due to their ubiquitous nature and remain unaffected during chemical treatments and remain dissolved in the wastewater. During physical treatments, like sedimentation and filtration, PFAS moves freely due to its hydrophilic nature evade all the filtration barrier and remains in the wastewater, and hence the treatment method also has to be chosen consciously depending type of PFAS targeted to remove, water quality, and total cost of the treatment method involved(20). This review focuses on some of the modern treatment technologies adopted for the removal of PFAS, like adsorption, membrane filtration, and advanced oxidation process (AOP), with detailed insights on their treatment efficiency and operational efficiency. All the methods reported have partially removed or degraded long-chain to short-chain PFAS but never completely removed PFAS from water. The following are the recent studies on PFAS removal using different methods.

Adsorption

Adsorption is an efficient method for separating various pollutants, including PFAS, and is regarded as a superior technology for water treatment due to its cost-effectiveness, environmental sustainability, high efficacy, simple design, ease of operation (25). Adsorption involves the accumulation of PFAS molecules through physical or chemical interaction. Adsorbents are designed not only to capture PFAS but also to degrade it. Granular Activated carbon (GAC), metal organic framework and ion exchange resin are some of the adsorbents that are discussed in this review paper. GAC is the most extensively studied adsorbent for PFAS removal due to its low cost, high efficiency, and easy synthesis methods. Electrostatic and hydrophobic interactions are the major removal mechanisms involved in the removal of PFAS from water by GAC (26). GAC has large surface area and are highly porous in nature it has two different pore like micropore with the size (< 2 nm) and mesopore (2-50 nm) and macropore (> 50 nm). For PFAS removal micropore and mesopore are considered to be effective, and also the adsorption efficiency of GAC mainly depends on the pore structure, which determines the accessibility of the internal surface for the adsorption of PFAS. Micropore is more suitable and shows higher affinity for long-chain PFAS compounds, and mesopore shows higher affinity for various shorter and more hydrophilic compounds. Recent studies on PFAS adsorption are mostly been done on PFOA and PFOS due to its wide usage in various industries. Recent studies in the characterization of nitrogen-grafted GAC it can be noted that the pore volume of the surface was modified two different modification methods were adapted to increase the functional groups which in turn increased the micropore structure. During nitric acid treatment oxygen containing functional groups like –COOH, –OH, –C=O were grafted into the surface which increased the hydrophilicity of the adsorbent followed ammonia treatment introduced functional groups $–NH_2$, –N= like led to the increased micropore volume from 0.381 cm^3/g to 0.413 cm^3/g which increased the adsorption capacity to these outcomes demonstrated the effectiveness of the tailoring stages in preserving pore space and significantly enhancing PFOA adsorption capability (27). In another study, the GAC was derived from bamboo with different pyrolysis temperatures and chemical activation conditions using potassium hydroxide. The obtained results

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show that increasing the ratio of KOH to carbon material from 2 to 6 increased the pore size from micropore to mesopore (2-4 nm). Mesopores are more suitable for compounds PFOA and PFOS due to their molecular length being 1.32 nm and 1.20 nm, which increases their molecular diffusion and the adsorption efficiency. In case of activation temperature increase, pore volume also increased in the range 2-4 nm, but with decreased surface area, which has lesser adsorption affinity for PFOS. This study highlights that pore volume, along with surface area, plays a crucial role in increasing the adsorption efficiency of long-chain molecules like PFOA and PFOS (28). Other commonly studied adsorbents are biochar and metal-organic frameworks. GAC has been used and reported widely, and its limitation in adsorption of short-chain PFAS is very prominent and cannot be overcome even with the various modifications and activation methods. Hence, better carbonaceous adsorbent materials were explored. Biochar has been acknowledged as an efficient medium for PFAS adsorption owing to its cost-effectiveness and sustainable nature, and ease of preparation. Biochar is abundant in aromatic and mineral constituents, produced through the pyrolysis of sustainably derived biomass under various conditions. The mechanism involved in the removal of PFAS compounds primarily involves electrostatic, hydrophobic, and π-π interactions. Hydrophobic interaction is the most reported mechanism in PFAS adsorption. The intensity of hydrophobic interactions correlates with the chain length of PFAS; the presence of long C–F chains in long-chain PFAS exhibits enhanced hydrophobicity (29). Pristine biochar also has certain limitations in the adsorption of short-chain PFAS due to its low surface area and porosity. To improve the biochar surface and its overall adsorption capacity, various modification methods like chemical modification using acid-base, metal doping, thermal and ball milling were adopted. Biochar that undergoes various modifications performs well in the aqueous environment and shows increased adsorption efficiency for both short and long-chain PFAS compounds (30). In recent studies, raw canola straw was chemically treated with phosphoric acid and zinc chloride to modify the biochar surface. The process parameters were optimized activator concentration, microwave power and microwave heating duration using Central Composite Design (CCD) to achieve higher adsorption capacity of PFAS. Activator concentration played a crucial role in the increase opening of more pore by breaking the structure and making more active sites. Heating time led to breaking more volatile compounds to form pores and microwave power speeds up the reaction and increases the porosity. The formation of pores was further confirmed by Brunauer–Emmett–Teller (BET) which showed increased pore volume after chemical treatment from 0.031 cm^3/g - 0.553 cm^3/g. Chemical and thermal modification enhances the pore structure, resulting in increased total pore volume and wider distribution of pore structure. A more porous structure is essential for PFOA adsorption, as it offers numerous pathways for PFOA molecules to adhere to the internal surface of biochar (31). Pyrolysis is another method widely used for biochar preparation. The temperature acts as a key factor in determining the pore size and specific surface area. When pyrolysis temperature is around the range of 400 °C the specific surface area and pore volume did not increase but when the temperature was raised to 800 °C the specific surface area raised to 554.3 m^2/g and total pore volume raised to 0.54 cm^3/g in most of biomass sources that are rich in cellulose, hemicellulose and lignin. The decomposition of lignin led to the formation of a stable pore structure at high temperatures. Lignin-rich biomass also produces high porosity and surface area in the biochar. High temperature also led to the development of stable micropores, which have higher adsorption capacity for the long-chain PFAS compounds (32). In another adsorption study conducted using reed straw-derived biochar (RESCA) for short chain PFAS compounds like PFBA, PFBS, PFHxA, the removal efficiency was in

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the range 81-89%. RESCA outdid GAC and anionic exchange resin, which only showed removal efficiency in the range 10-40% for short-chain compounds. The only parameter that was modified in the study was the high temperature for pyrolysis at 900°C and a heating time of 5 hours. The high temperature contributed to a rich carbonaceous surface with few functional groups like carboxyl and carbonyl, which led to the increased hydrophobicity of RESCA900. Specific surface area increased in volume to 730 m²/g and had a dominant mesopore (2-10 nm). The mesopore structure is very suitable for the adsorption of short-chain PFBA and PFBS. RESCA900 structure with high surface area and rich mesopore structure and hydrophobicity were the primary criteria for the efficient adsorption of short-chain PFAS compounds due to their well-matched molecular size of <2 nm (33). Metal organic frameworks (MOF) are another notable adsorbent in long and short chain PFAS removal. It is preferred due to its low cost, ease of synthesis, and tailoring according to pollutants that are removed and its reusability as an adsorbent. The important criteria for preferring MOF are due to their enormous surface area that provides more adsorption active sites for entrapping pollutants, and it also high porosity, which helps in the diffusion of more pollutants onto the surface of MOF (34). In a recent study on long chain PFOA removal the adsorbent metal organic framework was developed from a novel waste valorization where the red mud, rich in aluminium (Al^{3+}), used in industries, are used and strategically Al^{3+} was extracted to develop MOF in combination with linkers like terephthalic acid and trimesic acid in phase-controlled synthesis method with different ratio between the linker and the aluminium. MIL-100 exhibited a high surface area of 1189.15 m²/g, with more hydrophilic sites, which provide better accessibility for the adsorption of long-chain PFOA. Ion exchange was the dominant mechanism, with Lewis-base interaction showing the multifunctional adsorption potential of MOF (35). Ion exchange resins are also preferred as adsorbents due to their ease of operation, reusability after adsorption, and the fact that they do not produce any toxic byproducts. Anion exchange resins are efficient for adsorption due to their functional groups, polymeric matrix that is either steric or acrylic, cross-linkages, ion exchange capacity, and their particle size, making them a more suitable adsorbent for the removal of the PFAS from water (36). Four commercial anion exchange resins were studied for long-chain PFOA removal. HPA25M, which is a strong base resin with a high porous structure, showed high adsorption capacity of 97.9% for PFOA and 99.9% for PFOS in batch and real water samples, showing the resins' better tolerance and strong selectivity. Resin functional groups that are mostly quaternary ammonium and the mesopore structure, ranging from 1-10 nm were the key factors for faster diffusion, better access to binding sites, and enhanced interaction with the long chain bulky PFAS compounds (37). Limitations in using anion exchange resins are they are more expensive than other adsorbents and don't also show higher adsorption affinity for the short-chain PFAS compounds.

Membrane filtration

Membrane filtration technology in wastewater treatment is one of the advanced methods used in PFAS removal. High-pressure and low-pressure membranes are two different types of membranes used. The membranes are semi-permeable and utilized based on the size of the pollutant, its charge, and hydrophobicity. High-pressure membranes are reverse osmosis and nanofiltration, and low-pressure membranes are microfiltration and ultrafiltration. Among the membrane-based filtration, Reverse Osmosis (RO) and Nanofiltration (NF) are proven to be highly effective in the removal of PFAS across all chain lengths, with the rejection efficiency of 90%. NF has a pore size between 1 and 10nm, and RO membranes have a pore size less than 1nm,

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which is less compared to the PFAS compounds (38). The important mechanisms involved is size exclusion; the pore size of the semi-permeable membrane primarily influences the PFAS retention efficiency by steric size exclusion. In RO, high pressure applied also increases the pressure of the feed water treated, leading to an increase in its equilibrium or osmotic pressure and blockage of 90-95% of the molecules that are larger than the membrane pores. PFAS molecules are larger than the semipermeable membrane pore, which is around 1nm, leading to increased rejection efficiency (7). Nanofiltration offers a wide range of pores in the semipermeable membrane, ranging from 1 nm to 5 nm, and it requires less energy for the purification of any kind of contaminated water (39). Various studies are reported for PFAS removal using RO and NF. Cao et al.2025 carried out a notable study using five commercially available thin-film composite polyamide (PA) membranes for the removal of PFAS compounds by RO and NF methods. The membranes used were SW30 (RO), NF270 (NF), NF90 (NF), NFX(NF), DK (NF) selected due to their varying molecular weight cutoff (MWCOs) and rejection profiles. The six PFAS compounds were selected by the regulatory standards set by the USEPA 2024 (U.S. Safe Drinking Water Act) with varying chain lengths ranging from C4-C8, and to determine whether the chain length has any effect on the membrane, three PFAS compounds with varying chain lengths C4, C5, C10 were selected. RO membrane SW30 showed higher rejection, around 98.5% for all the PFAS implying the importance of the small pore size of the membranes. NF also showed higher rejection of 97% for all the selected PFAS but showed lower rejection efficiency for the short chain PFBA around 75.8% by NF270 and 96.7% for NFX indicating the difference in pore size of the membrane could vary the rejection efficiency. In case of chain length, the PFAS rejection efficiency increased with increasing chain length DK and NF90 showed higher rejection PFOA with 89.4% for DK and 98.9% for PFOS but DK showed reduced rejection efficiency for PFBA with 79.9%. the main mechanism involved in the efficient blocking of long-chain PFAS is due to the steric exclusion. High-performing membranes like NFX, NF90, and SW30 showed less difference in rejection efficiency between short and long PFAS due to their tighter pore structures. The study indicates that the membrane pore influences the removal of PFAS based on its chain length, and high-performing RO and NF membranes showed near complete rejection of PFAS regardless of its chain length (40). In another study by Ma et al. (2024), commercially available RO and NF membranes, specifically RO BW30–2540 and NF90–2540, were compared to determine their rejection efficiency. Short-chain PFBA and long-chain PFOA were selected to determine the different chain lengths of PFAS and their effect on the membranes used. Various parameters like ions, cationic and anionic surfactants, and operational temperature, were checked for their effect on rejection efficiency. RO membrane BW30–2540 did not have any effect from surfactants, coexisting ions, operational temperature, and rejection efficiency remained higher for the PFBA and PFOA. The main mechanism was size exclusion for RO. NF90–2540 membrane showed significant changes in the rejection efficiency by the various factors. The surfactants accumulated that lowering the membrane permeate flux which fouled the NF membrane, slowing down the flow of PFAS. CTAB, being positively charged forms a complex with PFAS, forming a complex with increased molecular size and increasing the rejection thus increasing the rejection efficiency. The presence of ions slightly increased when the valence ion valence increased from +1 to +3 and decreased when ion valence decreased from -1 to -3. The ions formed a cation-PFAS complex which increased the rejection efficiency for NF. Al^{3+} showed a significant change in rejection efficiency due to complexation. Temperature has effect on the membranes during the filtration process higher temperatures may cause the expansion of the polymeric

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membrane, decreasing water viscosity and more diffusion of solutes across the pores, decreasing the rejection of PFAS. In the current study increase in solution temperature from 15 to 45 °C rejection of PFBA by NF decreased but rejection efficiency of PFOA did not have any impact when the solution temperature increased. High temperature also increased the mean free path of PFAS leading to more collision with NF membrane pores and enhanced Knudsen diffusion. Short chain PFBA exhibited high Knudsen number (2.01–2.82) than long chain PFOA (1.38–1.93). Thus temperature has effect on the NF membrane compared to RF (41). The rejection efficiency of the membrane provides insights into the semipermeable membrane efficiency and the relationship between the membrane properties and its separation efficiency. the compact structure of RO membrane is also the main criterion for its better performance than nanofiltration. Though both methods show high rejection efficiency, RO is superior and has more efficiency for the removal of short-chain and long-chain PFAS.

Advanced Oxidation Process (AOP)

Advanced Oxidation Process (AOP) is a class of destructive treatment method and very much different from conventional and advanced wastewater treatment methods like adsorption, ultrafiltration, Reverse osmosis, and coagulation. AOPs generate the Reactive Oxygen Species (ROS), which are free radicals capable of degrading recalcitrant PFAS compounds. There are different free radicals are among which the hydroxyl radical (OH·) is highly reactive and potent. ROS determines the defluorination and destruction of PFAS (42). Hydroxyl radicals attack polar functional head group like the carboxylate group in PFOA or the sulfonate group in PFOS. Other free radicals target the C-F bonds in the perfluoroalkyl chain and cause defluorination. AOP are designed using catalyst or energy like electricity, light. The in-situ methods involving electricity and light are low-cost and more eco-friendly. Photocatalytic methos like UV photolysis and electrochemical oxidation methods are most preferred in the destruction of PFAS (43). The recent study on the destruction of PFAS using a catalyst was reported by Gu.et al, 2025. The long-chain PFOA was selected for the study. FeOCl/(Bi-MOF-BiOCl)$_{100}$ was a composite catalyst designed with oxygen defects. The removal efficiency of PFOA of the composite catalyst was compared with FeOCl (Iron oxychloride), which is a quasi-two-dimensional material. The photocatalytic activity of the catalyst was determined in the degradation of PFOA with UV radiation at 253.7 nm within 240 minutes. Initially catalyst was allowed to absorb the PFOA for 30 minutes, after 30 minutes it was noted that the Iron oxychloride alone adsorbed 55.5% of PFOA and FeOCl/(Bi-MOF-BiOCl)$_{100}$ 94.3 % PFOA. Followed by UV irradiation FeOCl removed 65.7% PFOA and FeOCl/(Bi-MOF-BiOCl)$_{100}$ removed 99.9 % PFOA. When Bi-MOF ratio was altered to 200 the FeOCl/(Bi-MOF-BiOCl)$_{200}$ showed decreased removal efficiency of 86.9 %. Defluorination of PFOA in C-F bond was very low for FeOCl with 15.7 % and FeOCl/(Bi-MOF-BiOCl)$_{100}$ showed 36.2 % defluorination, but decreased to 24.1 % when excess Bi-MOF was used after 240 minutes. The main mechanism behind the degradation of PFOA was cleavage of carboxyl group and releasing of CO_2 (decarboxylation) and substitution of hydrogen in place of fluorine in a sequential manner (H/F exchange) (44). UV/sulfite system degradation for five different PFAS was done in the novel study using gel type (A532E, A600) and microporous resins (A860). Short-chain like PFPrA, PFHxA, and long-chain like PFOA, PFOS, and GenX to understand the significant impact on the chain size of PFAS during the UV/sulfite-assisted defluorination. The resins selected were first studied for its adsorption efficiency followed by selection of the resin that showed higher adsorption capacity, and finally degraded using UV/sulfite photocatalysis. Among the different resins, A532E showed higher adsorption efficiency for short chains and

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A600 showed higher adsorption efficiency for long chain. Electrostatic interaction was the mechanism behind the short chain and hydrophobic interaction for long chain. Steric effects hindered the adsorption of long chain due to the presence of functional groups. For desorption studies resins A600 and A860 which showed better adsorption for most of short and long chain. 0.025% NaOH desorption effluents were treated using UV/sulfite system after 24 hours 98.7% degradation of PFPrA and absence of PFHxA and GenX. The degradation efficiency achieved for the selected PFAS were 96.7-100% and defluorination achieved in the range 46.6-86.1% (45). Photocatalytic ozonation was done by Laushk et al.2022 using WO_3/TiO_2 catalyst five different PFAS, namely PFOA, PFHxS, PFBS, GenX, and 6:2 FTS. Ozonation was initially done to assess the ability to degrade PFAS and it had only 4% removal even at high doses of ozone. Then, photocatalysis showed 84.6% for all the PFAS compounds. and when only photolysis was carried out in the absence of catalyst the removal efficiency was 78.5% PFOA, 85.5% PFHxS, and 73.6% for 6:2 FTS. When photocatalysis ozonation was done, 74.5% of PFAS were removed. GEN X showed the highest removal in ozone photolysis, degrading 85.2% compared to photocatalysis and photocatalytic ozonation, which showed 72.3% and 74.3%. different methods provided different degradation efficiencies and photocatalysis coupled with ozonation showed better removal efficiency for PFAS (46). Electrochemical oxidation is other method that are widely studied for the degradation and removal of PFAS. There are two methods direct electrochemical oxidation and indirect electrochemical oxidation. In direct electro oxidation occurs on the surface of the electrode and direct transfer of electrons and it depend on the in-situ generation of ROS and leading to the direct transfer of electrons from PFAS to the anode. In direct electro oxidation, the electrons behave as mediators and help in the generation of ROS (47). A recent study was done to degrade 29 PFAS including short and long chain using Fenton assisted electrochemical oxidation using Platinum cathode and two different anodes Ti/BDD and Ti/IrO_2. The study was done on stimulated PFAS water. Among both anodes used Ti/BDD showed the highest removal in the range of 86.1–100% across different PFAS groups. Ti/IrO_2 required higher operational inputs and showed less removal efficiency and the removal efficiency only increased in the range only there was higher operational inputs 54.5–98.1%. hydroxyl radical produced during the oxidation degraded both short and long chain PFAS among both groups long chain PFAS like PFCAs and PFSAs showed more resistance during degradation. The proposed mechanism was hydrolysis in degrading both PFBS and intermediate compounds (48).

Future outlook and research direction

Growing concern about PFAS contamination and its ill effects on living organisms, various methods and technologies are being adopted for its degradation and elimination from water matrices. But various limitations are observed in the methods adopted, and no technology has offered a complete method to eliminate PFAS. Methods like adsorption do not defluorinated or degrade PFAS, methods like Advanced Oxidation Process are not cost-effective and consume more energy, and are not sustainable, and hence it's important to shift to hybrid methods that incorporate different technologies to overcome the limitations. The future research must focus on developing methods that can maximize overall efficiency in the degradation of PFAS with minimum operational costs and complete removal from the water matrices. The other important area to be addressed is the ineffectiveness and struggles associated with the removal of short chain PFAS compounds by conventional methods. Development of materials or hybrid technology for the removal of short-chain PFAS should be given priority. The cost-effective and sustainable material development, eco-friendly, like plant-based materials rich in lignocellulosic substance,

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and nanomaterials, has to explored with its modification techniques, providing high removal efficiency for PFAS has to be developed. Effective treatment is also linked to the real time monitoring and accurate detection of the PFAS. Various methods have to be developed for the detection in environmental matrices. Thus overall the approach for the better PFAS future research is the development of sustainable and hybrid technology and materials for the complete removal of PFAS from water matrices.

Conclusion

PFAS contamination in water matrices has led to increased disruption in the environment at different levels and also a significant impact on humans and other organisms. Its detection and degradation had become a global challenge due to its recalcitrant nature. PFAS continuous use in different industries also led to contamination of water and accumulation in living organisms, raising continuous health concerns. The mini review highlights the advanced treatment methods their limitations in the treatment and degradation of forever chemicals. Adsorption technology with different engineered materials offered an efficiency in effectively removing long chain PFAS and could not offer higher removal rates for short-chain PFAS. Granular activated carbon, modified biochar and metal-organic framework showed good removal performance for adsorption. Membrane-based filtration, like nanofiltration and reverse osmosis, also offered a higher rejection efficiency in removing short and long-chain PFAS, with limitations like brine stream production, which requires additional treatment. Advanced oxidation process like UV-based removal and electrochemical oxidation, which are destructive methods were also discussed to understand the mechanism of cleavage of C-F bonds and help in the complete degradation of PFAS. Advances in the treatment of PFAS help to overcome the challenges faced in contaminated water treatment. More importance in the removal and degradation of short chain PFAS has been discussed. Future outlook and research scope should mainly focus on developing integrated treatment technologies and adsorbent materials that will offering sustainable treatment methods. Effective removal of PFAS is crucial for environmental and human health, and hence continued research is important to develop sustainable treatment technologies.

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