Chapter 3
World Profile of Foreseeable Strategies for the Removal of Per- and Polyfluoroalkyl Substances (PFASs) from Water

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Abstract Per- and polyfluoroalkyl substances (PFASs) have been used in wide range of industries and daily life and therefore released into the aqueous environment. Due to their unique properties, such as environmental persistence, bioaccumulation, and toxicity, PFASs have drawn increasing concern in recent years. PFASs-contaminated water has adverse effects on water microorganisms and aquatic life as well as human life. So far, tremendous efforts have been made on PFASs pollution and their treatment, yet most of the efforts have been spent on laboratory experiments. Their feasibility, cost-effectiveness, and field applicability are questionable. This review examined studies on existing while updated treatment technologies, with the goal of providing an outlook on these technologies and more importantly, proposing the most likely technique. As such, a constructed wetland-microbial fuel cell (CW-MFC) technology was recommended, which is a newly emerged technology by integrating physical, chemical, and enhanced biological processes plus the wetland plants' functions with strong eco-friendly features for the comprehensive removal of PFASs. The roles of wetland plants, substrates, and electroactive bacteria (EAB) in the removal of PFASs in the CW-MFC system were discussed with focus on highlighting the different mechanisms. It is expected that the review can strengthen our understanding of PFASs' research and thus can help select reasonable technical means of aqueous PFASs control.

Keywords Per- and polyfluoroalkyl substances · Water treatment · Degradation technologies · Construct wetlands · Microbial fuel cell

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3.1 Introduction

Per- and polyfluoroalkyl substances (PFASs) are a group of synthetic chemicals comprising more than 9000 chemicals (Cordner et al. 2021). Due to their unique hydrophobic/lipophobic physicochemical properties, they have a wide range of industrial and consumer applications such as packaging materials, waterproof material, electronics, polishes, and aqueous film-forming foams (AFFFs) (Naidu et al. 2020). PFASs have been developed for more than seven decades with the different types of fluoropolymers over 230,000 tons/year worldwide for the moment (Zhang et al. 2022). PFASs are released into the environment as a result of their widespread manufacture and application both purposefully and unintentionally. Due to persistent (P), bioaccumulative (B), and toxic (T) properties, as well as long-range transport potential (LRTP), PFASs have been detected in different environments (such as water, soil, and aerosols), which have caused great concern among the scientific community and the public. Previous studies have reported that PFASs have been linked to a slew of negative health effects in both animal and human (Naidu et al. 2020; Silva et al. 2021; Teymourian et al. 2021). Therefore, when PFASs enter the environment, they are labeled as "contaminants of emergent concerns (CECs)."

Water environment is regarded as a significant sink and source for PFASs. Many researchers have conducted a series of studies on the content level, distribution characteristics, influencing factors, and environmental behavior of PFASs in aqueous environment in recent years (Macorps et al. 2022; Pistocchi and Loos 2009; Szabo et al. 2018). In order to control and reduce the environmental risk of PFASs, some remediation technologies and methods have been tested, such as coagulation, adsorption, membrane separation, photodegradation, and hydrothermal as well as microbial degradation (Hao et al. 2022; Oyetade et al. 2018; Zhuo et al. 2020). It should be noted that these approaches have both advantages and disadvantages in foreseeable applications. When it comes to controlling or removing PFASs from water, integrated technologies are thought to be more effective than solo techniques.

Constructed wetlands (CWs) are widely applied across the world due to their cost-effectiveness and satisfactory treatment effects. CWs use plants, substrates (soil, sand, and gravel), microbial and interaction processes to remove contaminants in wastewater with minimal dependence on mechanical elements. So far, CW system has been proven effectively to removal CECs and persistent organic pollutants (POPs) in the aqueous environment (Li et al. 2014; Matamoros et al. 2008; Vymazal and Březinová 2015). In recent years, a novel technique of introducing microbial fuel cell (MFC) into CW to form CW-MFC has been studied. Compared with conventional CW, CW-MFC system is more powerful in removing several hard- or non-degradable contaminants (Wang et al. 2019a; Zhang et al. 2018). To the best of our knowledge, rare information exists on foreseeable strategies for the removal of PFASs from water in CW-MFC system.

This review covers the state of the art and understanding of treatment strategies for PFASs from water environment after briefly describing their characteristics, hazards, and challenges. Moreover, this review focuses on the potential of employing CW-MFC system for PFASs removal. The knowledge provided in this review is hoped to improve our understanding of PFASs research and aid in the selection of suitable technological ways of aqueous PFASs control.

3.2 Overview of PFASs in Water Environment

3.2.1 Properties

PFASs are organofluorine compounds with alkyl chain as the skeleton and hydrogen atom partially or completely replaced by fluorine atom, which can vary in chain length and linear or branched isomers (Buck et al. 2011). The general chemical formula of PFASs is F(CF2)n-R, where R is hydrophilic functional group. Recently, according to the Organization for Economic Cooperation and Development, "*PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e., with a few noted exceptions, any chemical with at least a perfluorinated methyl group* ($-CF_3$) *or a perfluorinated methylene group* ($-CF_2-$) *is a PFAS*" (Wang et al. 2021). All the PFASs have the structure of a C–F bond, which is extremely polar, strong, and stable, giving PFASs exceptional chemical properties such as extremely high thermal and chemical stability. Perfluoroalkyl acids (PFAAs) are the most important and basic PFASs molecule, which are divided into two groups: perfluoroalkyl sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs). The most frequently detected PFSAs and PFCAs in the water environment are perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), respectively (Podder et al. 2021).

Regarding the carbon chain length of PFASs, PFASs can further divide into two main categories, the long-chain PFASs (the carbon number ≥ 8 with PFCAs, and ≥ 7 with PFSAs) and the short-chain PFASs (Fig. 3.1). With different chain length and hydrophilic functional group, PFASs have unique properties. As explained, for example, the short-chain PFASs, such as perfluorobutanoic acid (PFBA), are highly soluble with lower sorption tendency in soil, which leads to greater mobility and bioaccumulation than that of the long-chain PFASs in the environment (Teymourian et al. 2021; Macorps et al. 2022).

Concerns about the potential environmental issues and human hazard impact of PFASs have been investigated. Researchers have well-documented that the toxicities of PFASs involve muscle, liver, reproduction and development, neurotoxicity and potential carcinogenicity (Sunderland et al. 2019), while the arithmetic and geometric mean half-lives of serum elimination are 5.4 years for PFOS, and 3.8 years for PFOA, respectively (Olsen et al. 2007). The main exposure pathways for human may include drinking contaminated water, eating contaminated foods, and inhalation of some neutral volatile PFASs, such as fluorotelomer alcohols (FTOHs). In terms of environmental risk assessment, there has been a rise in ecological toxicity studies

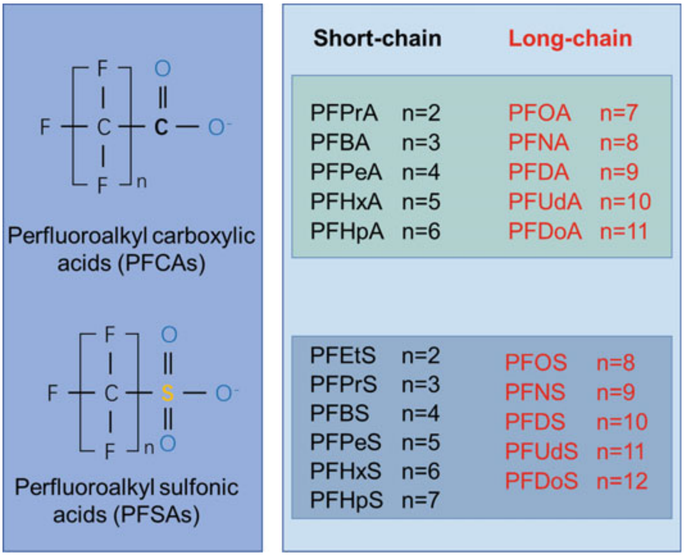

Fig. 3.1 Typical classification of PFASs

as researchers attempt to understand the impacts of PFASs on various ecosystems (Zhang et al. 2022; Cai et al. 2019). However, evaluating the toxicity of PFASs involves a number of obstacles, not the least of which being the diversity of PFASs compounds, as well as variances in their mechanisms of action in different animals. According to Sinclair et al. (2020) who reviewed the PFASs toxicity data in invertebrates, fish, and amphibians, the concentrations that induced mortality in 50% (LC_{50}) of the studied population of PFASs are unlikely to occur in the outside environment. To move forward, scientists must bridge the data gap between laboratory exposures and the actual environmental concentration.

3.2.2 Occurrence of PFASs in Water Environment

Monitoring the occurrence of PFASs in the water environment has recently become a major concern in the world. PFASs have been widely detected in wastewater, surface water, and groundwater, and even drinkable bottle water (Table 3.1).

The domestic and industrial wastewater and landfill leachate are the major sources of PFASs in water environment. As shown in Table 3.1, the high total concentrations of PFASs (0.2–6000 μg/L) were found in the wastewater from the chrome plating industry (Qu et al. 2020). Moreover, more than 800 μg/L of PFASs was detected in the effluent of electroplating wastewater treatment plant (WWTP) although this electroplating WWTP had ultrafiltration (UF) and reverse osmosis (RO) processes (Qu et al. 2020). On the other hand, landfill leachate is a significant source of high

Table 3.1 Detection and investigation of PFASs in water environment

Water environment	Main compounds	PFASs analyte count	Total concentration (ng/L)	Reference
Municipal wastewater treatment plant (WWTP)	PFOS, 6:2 Cl-PFAES	4	1610–153,000	Qu et al. (2020)
Municipal WWTP	PFOA, PFOS	3–17	1030–3360	Masoner et al. (2020)
Municipal WWTP	PFOA, PFBA	21	9.3–520	Coggan et al. (2019)
Municipal WWTP	PFBA, PFHxA	27	16–1400	Lu et al. (2021)
Landfill leachate	PFHxA	21–31	19,800–48,700	Masoner et al. (2020)
Landfill leachate	PFBS	7	0.1–17,000	Harrad et al. (2019)
Industrial wastewater	6:2 Cl-PFESA, 8:2 Cl-PFESA	17	2100–4200	Liu et al. (2022)
Industry wastewater	PFOS, 6:2 Cl-PFAES	7	200–6,000,000	Qu et al. (2020)
Seawater	PFOA	21	0.98–2.64	Xiao et al. (2021)
Seawater	PFBA, PFOA	20	0.125–1015	Wang et al. (2019b)
River	PFOS, 6:2 Cl-PFAES, 6:2 FTS, PFOA	4	400–2300	Qu et al. (2020)
River	PFOA, PFOS, PFHxA	14	0.04–31.3	Cai et al. (2022)
River	PFOA, PFBA	15	11.8–281	Li et al. (2022)
River	PFOA	13	0.8–274.6	Dong et al. (2020)
Lake	PFPeA, PFHxA	16	17.7–467.0	Lee et al. (2020)
Lake	PFHxS	13	30.45–1563	An et al. (2021)
Groundwater	PFOS	3	1.9–2.4	Qu et al. (2020)
Groundwater	PFOS, PFBA	24	31.4–15,656.0	Gao et al. (2019)
Drinking Water	PFOA, PFOS	9	1.36–20.2	Jiang et al. (2021)
Drinking water	PFBA, PFHxA	6	11.8–59.7	Gao et al. (2019)
Drinking water	PFBA, PFOA	17	9.29–266.68	Chen et al. (2019a)
Bottle water	PFPrA, PFCA	32	0.17–18.87	Chow et al. (2021)

PFASs concentrations. In a study, more than 20 types of PFASs were found in landfill leachate with a total concentration of 93,100 ng/L, which was an order of magnitude greater than the influent and effluent of the WWTP receiving this landfill leachate (Masoner et al. 2020). Compared with industrial wastewater and landfill leachate, the concentrations of PFASs in domestic wastewater are generally lower. Many home products, such as fast food containers/wraps, cleaning products, and non-stick cookware, contain PFASs and release them into wastewater after usage. Coggan et al. (2019) investigated the PFASs in the influent and effluent of nineteen Australian WWTPs with varied sizes, capacities, localities, and treatment types. The results demonstrated that the range of PFASs concentrations in WWTPs influent and effluent was 9.3–520 ng/L, and there were no significant PFASs removals after WWTPs.

It is worth noting that most conventional WWTPs were not capable to remove PFASs. Thus, a considerable amount of PFASs-containing wastewater is discharged into natural water bodies, resulting in surface water and groundwater pollution. In the Asan Lake of South Korea, the 19 PFASs were detected with the total average concentration of 17.7–467.0 ng/L, the wastewater from the nearby industrial parks may be a major source of PFASs in the lake (Lee et al. 2020). Similarly, the average concentrations of PFASs in Tai Lake in China in 2018 and 2019 were 205.6 ng/L and 171.9 ng/L, respectively, while the study also suggested that the local industry was the main source of PFASs (An et al. 2021). Furthermore, the vertical transfer in soil and water bodies contaminated by PFASs leads to groundwater contamination. One study found that the total concentrations of PFAAs range from 31.4 to 15,656.0 ng/L in groundwater sample, with short-chain PFAAs being the most frequent (Gao et al. 2019). This study also found that the concentration of PFASs in groundwater decreased with increasing distance from the manufactory.

The presence of PFAS in drinking and bottled water seems inevitable due to the ubiquitous occurrence of PFASs in surface and groundwater, especially because present technologies of drinking water treatment plants (DWTPs) are incapable to completely remove PFASs. Research in Ireland found that PFOS, PFOA, PFBS, and PFHxS were all discovered in tap water from homes and offices (Harrad et al. 2019). Chen et al. (2019a) further investigated the occurrence and transport behaviors of PFASs in drinking water distribution systems (DWDS), they detected 17 kinds of PFAAs in the tap water with the average concentrations ranging from 9.29 to 266.68 ng/L. The results also found that the fate and migration of PFASs in the DWDS were influenced by their physicochemical characteristics and the sediments in the system. According to the results of PFASs in bottle water research done in the USA (Chow et al. 2021), the total PFASs concentration in 39 examined samples was 0.17–18.87 ng/L while 97% of samples were below 5 ng/L.

Overall, these studies suggest that PFASs are already widespread in a wide range of water environment. The government should take necessary and immediate action to set up relevant regulation for PFAS removal/control.

3.2.3 *Protocols of PFASs in Drinking Water*

PFASs are widespread in aquatic environments and have been associated with human and animal health. They are difficult to degrade in nature. As a result, some countries and local/state governments have enacted legislation/protocol to limit the concentration of PFASs in drinking water. Table 3.2 lists the updated information.

The US Environmental Protection Agency (EPA) proposed PFASs drinking water restrictions in 2016 with maximum contamination levels (MCLs) of 70 ng/L for either PFOS, PFOA, or their total. Some states in the USA also have strict or loose regulations of PFAS in drinking water (Table 3.2). National regulations

Table 3.2 Global protocol for limiting the amount of PFASs in drinking water

Country/state	PFOA (ng/L)	PFOS (ng/L)	Year of action
US EPA (https://www.epa.gov/sdwa/drinking-water-health-advisories-pfoa-and-pfos)	70	70	2016
California (https://www.jdsupra.com/legalnews/pfas-update-state-by-state-regulation-4639985/)	5.1	6.5	2021
Minnesota (https://www.jdsupra.com/legalnews/pfas-update-state-by-state-regulation-4639985/)	–	15	2019
New York (https://www.jdsupra.com/legalnews/pfas-update-state-by-state-regulation-4639985/)	10	10	2020
Massachusetts (https://www.jdsupra.com/legalnews/pfas-update-state-by-state-regulation-4639985/)	20	20	2018
Canada (https://www.canada.ca/en/health-canada/programs/consultation-perfluorooctanoic-acid-pfoa-in-drinking-water/document.html)	200	600	2018
Denmark (https://www2.mst.dk/Udgiv/publications/2015/04/978-87-93283-01-5.pdf)	300	100	2015
Germany (https://www2.mst.dk/Udgiv/publications/2015/04/978-87-93283-01-5.pdf)	300	300	2006
Sweden (https://www2.mst.dk/Udgiv/publications/2015/04/978-87-93283-01-5.pdf)	90	90	2014
Netherlands (Kurwadkar et al. 2022)	390	200	2020
United Kingdom (https://www.dwi.gov.uk/en/private-water-supplies/pws-installations/guidance-on-the-water-supply-water-quality-regulations-2016-specific-to-pfos-perfluorooctane-sulphonate-and-pfoa-perfluorooctanoic-acid-concentrations-in-drinking-water/)	10	10	2021
Australia (https://www.pfas.gov.au/government-action/pfas-food-water)	560	70	2017
China (https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=99E9C17E3547A3C0CE2FD1FFD9F2F7BE)	80	40	2022

on PFASs in drinking water vary greatly throughout the world. The MCLs for PFOA and PFOS in Canadian drinking water are 200 and 600 ng/L, respectively (https://www.canada.ca/en/health-canada/programs/consultation-perfluorooctanoic-acid-pfoa-in-drinking-water/document.html), but the MCLs for these two compounds in the UK are only 10 ng/L (https://www2.mst.dk/Udgiv/publications/2015/04/978-87-93283-01-5.pdf). Most recently, the Chinese government announces a new "Standard for drinking water quality (GB 5749-2022)," which limits the values of PFOA and PFOS in drinking water of 80 ng/L and 40 ng/L, respectively (https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=99E9C17E3547A3C0CE2FD1FFD9F2F7BE). Although PFAS concentration in drinking water has been subjected to a variety of regulatory laws and standards up to this point, it is important to keep in mind that PFASs are consistently harmful to humans. It is critical to implement corresponding regulations in some developing nations and regions to limit PFASs contamination in drinking water, as well as more comprehensive national collaboration.

3.3 Treatment Technologies for PFASs in Water

As "forever chemical," the treatment technologies for PFASs in water environment can be divided into separation technologies and destruction/degradation technologies. The main separation technologies include adsorption and membrane filtration, while thermal treatment, advanced oxidation/reduction, hydrothermal, and biological technologies are potential to the destruction of PFASs.

3.3.1 Adsorption

Adsorption is the most frequently investigated and employed treatment technology. It has been used for both ex-situ and in-situ water treatment applications. Various adsorbent materials have been tested regarding the removal performance of PFASs from water (Zhang et al. 2019a). Granular activated carbon (GAC) is considered as efficient and more economic sorbent with good performance (normally > 90%) in controlling aqueous PFASs. For example, the average removal efficiency of 15 PFASs in a full-scale DWTP with GAC as filter was from 92 to 100% (Belkouteb et al. 2020). A review of the PFASs adsorption performance of commercial carbon materials found that GAC has an adsorption capacity in the tens to hundreds of mg/g range (Pauletto and Bandosz 2022). Although powdered activated carbon (PAC) has a better adsorption capacity for PFASs than that of GAC (Zhang et al. 2019a), it has intrinsic disadvantages such as regeneration and reutilization. The impact of sorption, on the other hand, differs depending on the type of PFASs. For different PFASs, GAC/PAC has a variable adsorption capability and breakthrough time. Because the sulfonate group is more readily adsorbed onto oxide surfaces than the carboxylate group, PFSAs tend to adsorb more strongly than PFCAs with equal chain length (Du et al. 2014; Wang et al. 2012), whereas the adsorption of branched isomers is smaller than linear (McCleaf et al. 2017).

Other adsorbents, such as resins (McCleaf et al. 2017), cyclodextrin polymers (Ching et al. 2022), biochar (Sørmo et al. 2021; Xiao et al. 2017), and metal-organic frameworks (MOFs) (Pauletto and Bandosz 2022) have been tested in recent years to remove PFASs from water. It is worth noted that the properties of adsorbents and the kind of PFASs, as well as the environmental factors (i.e., solution pH, surface charge, dissolved organic matter, inorganic ions) can significantly affect the adsorption process (Oliver et al. 2019; Qi et al. 2022). When hydrophobic interaction is the primary mechanism in adsorption, short C–F chain PFASs have a more hydrophilic character as well as a smaller molecular size, resulting in a quick breakthrough time and low removal efficiency (Li et al. 2019a).

Electrocoagulation (EC) is another adsorption reaction-based technique for PFASs removal. The main mechanism of EC is adsorption of contaminants with metal hydroxide flocs which are formed by the soluble metal anode (e.g., Fe, Al, Zn) under the action of an applied electric field. At high influent concentrations (0.25 mM), a study using an air cathode in an electrocoagulation reactor demonstrated excellent PFOA removal efficiency (approximately 100%), whereas PFOS removal at low concentrations (0.1 μM) was superior than PFOA removal (Mu et al. 2021). In addition, the anode metal materials are the key to the electrocoagulation process. Liu et al. (2018) investigated the EC technique using Al-Zn electrodes for the removal of PFOA. The results achieved over 99% removal under 1 mg/L influent concentration.

Although adsorption appears to be a well-established method for PFASs removal, there are certain disadvantages to adsorption investigations to date. The majority of research has focused on the removal of a particular kind of legacy PFASs (i.e., PFOA and PFOS), despite the fact that the aquatic environment contains a variety of emerging PFASs with various functional groups and chain lengths (Oyetade et al. 2018; Zhang et al. 2019a, 2021). Furthermore, the effects of various organic matter components, inorganic ions, and microbials in water or wastewater must be investigated further. Adsorbents utilized to remove PFASs, on the other hand, should be carefully evaluated for disposal or regeneration after saturation. Information on the long-term stable adsorption of aqueous PFASs at full scale is particularly needed from an engineering standpoint.

3.3.2 Membrane Filtration

The membrane filtration, such as the reverse osmosis (RO) and nanofiltration (NF), achieves remarkable removal of aqueous PFASs (Wang et al. 2018). NF membranes have been used to remove various types of PFASs from water in several studies. They have been found to be particularly effective in removing PFASs regardless of chain length or functional group (Wang et al. 2018; Léniz-Pizarro et al. 2022;

Mastropietro et al. 2021; Xiong et al. 2021). PFOS and perfluorobutane sulfonate (PFBS) through NF (piperazine amide) membrane showed high retention rate with about 90% (Wang et al. 2018). RO is effective in the removal of mainly organic and inorganic contaminants from water and has been employed in industrial water treatment around the world. Regarding PFOS removal in water, RO membrane is better than NF (Tang et al. 2007). However, the ionic strength and solution pH significantly affected retention rate of membrane filtration process. In addition, the pretreatment processes (such as coagulation/flocculation–precipitation, adsorption) are important to avoid fouling with RO and NF to remove PFASs. Furthermore, high-pressure pumps are required to give transmembrane power to RO and NF, which subsequently hold fluid with high concentrations of PFASs. Another key question is how to manage and dispose of this hazardous liquid. The treatment train consisted of RO or NF filtration separation and degradative/destructive technologies have been recommended. This combination of several removal procedures improves removal efficiency while lowering costs and reducing hazardous by-product (Lu et al. 2020).

3.3.3 Destructive Techniques

3.3.3.1 Advanced Oxidation and Reduction

Advanced oxidation processes (AOPs) can form highly oxidizing species, like ozone (O_3), hydroxyl radicals ($HO^\bullet$), persulfate ($S_2O_8{}^{2-}$), sulfate radical anions ($SO_4{}^\bullet$), hydroperoxide ($HO_2{}^\bullet$), and superoxide ($O_2{}^\bullet$) ions, though oxidant activation with solar radiation, heat, and catalysts. However, because $HO^\bullet$ and O_3 do not destroy the C–F bond, they are unable to fully breakdown PFOA/PFOS (Qi et al. 2022). Sulfate or/and persulfate generated can successfully breakdown PFOA under a range of circumstances, according to several lab-scale research (Wu et al. 2018; Zhang et al. 2019b). Several shorter-chain PFAAs, such as perfluoroheptanoic acid (PFHpA) and PFBA, were generated by the loss of CF_2 units from PFOA with persulfate reaction (Bai et al. 2022). Although other studies have shown that ultrasonic treatment (Lei et al. 2020), persulfate photolysis (Li et al. 2019a), photocatalysis (Jin et al. 2014; Qian et al. 2021), sonochemical (Cao et al. 2020; Rodriguez-Freire et al. 2015), and Fenton (Santos et al. 2016) can be used to destroy PFASs, these studies mostly require strict operating conditions. This suggested that, in the field application, generating highly oxidizing species to remove PFASs might be difficult due to unreasonably high costs and sluggish reaction rates.

Several studies reported that zero-valent metals can be employed to eliminate PFASs by chemical reduction (Arvaniti et al. 2015; Chen et al. 2020; Hori et al. 2008). Hori et al. (2008) used subcritical water and zero-valent iron (ZVI) to breakdown PFASs at high pressure (20 MPa) and temperature (350 °C). The results revealed that the ZVI powder accelerated the breakdown of PFOS into F ions. Following that, other investigations revealed that PFOS and PFOA were destroyed at 380 °C, with yields of 9.2% fluorine and 21.9% sulfate, respectively. The ZVI surface area was shown to be linked with PFASs degradation rates, indicating that the reaction is surface catalyzed. This technique, like AOPs, needs more energy and appropriate reaction circumstances. Recently, Chen et al. (2019b, 2020) discovered that hydrated electrons can quickly destroy PFOA and PFOS under UV irradiation with surfactants. They suggest that hydrated electrons generated by photo-irradiation can attack C–F bonds under ambient environments, enabling defluorination and mineralization of PFASs in actual wastewater. However, there is currently a lack of long-term and field-scale application for this technique.

Several chemical redox technologies have also been shown to reduce PFASs contamination in laboratories. There are several considerations in a full-scale application. To begin with it, the factional group (carboxylic or sulfonic) of PFASs is more susceptible to redox transition than the C–F bond, resulting in the parent compound's partial transformation (Anumol et al. 2016). It will produce various intermediates, such as short-chain PFAAs, as well as potentially more mobile or hazardous substrates. Secondly, typical co-contaminants in wastewater would have an influence on the removal of PFASs and the generation of by-products (Mu et al. 2021). Furthermore, oxidizing species are more susceptible to readily oxidized other pollutants as well as self-quenching (Lenka et al. 2021; Ross et al. 2018).

3.3.3.2 Thermal Treatment

Incineration is usually used to destroy organic compounds, especially hazardous contaminants. Due to high stability of C–F bond, the PFASs have been used to produce aqueous film-forming foam (AFFF) and non-stick cookware. Incineration process to handle PFASs, therefore, must be capable of destruction of the C–F bond. To convert PFASs into HF and non-fluorinated compounds, thermal treatment is required at high temperatures (> 700 °C) for an extended length of time (Khan et al. 2020). Moreover, the greenhouse gases (GHGs), such as hexafluoroethane and tetrafluoromethane, may be formed during the incineration treatment of PFOS (Ahmed et al. 2020). High-temperature thermal treatment, on the other hand, consumes a range of fossil energy. Therefore, lowering the temperature of PFAS thermal treatment is a potential way. Wu et al. (2019) promised a novel thermal treatment technology for achieving rapid and complete destruction of PFOS via alkaline hydrothermal reaction under temperature with 200–350 °C and pressures with 2–16.5 MPa. They found that complete conversion of C–F bonds to F^- within 40 min for the hydrothermal reaction with 1 M NaOH. However, the intermediates and by-products may lead to secondly environmental risk. Generally, the thermal processes have yet to be proven at scale, where inefficiencies might impair performance. In addition, the incompletely destroyed of PFASs may form a potential source of air pollution.

3.3.3.3 Electrochemical Reaction

Electrochemical oxidation is the electrochemical approaches that have been proven to be effective in PFASs removal from water (Zhuo et al. 2020; Gomez-Ruiz et al. 2017). The direct oxidation of the anode or/and the indirect oxidation of active radicals are the mechanisms of electrochemical oxidation to PFASs removal (Niu et al. 2016). The removal efficiency is substantially determined by the anode material's electron transfer capacity, $^{\bullet}$OH-generating ability, and oxygen evolution potential (OEP) (Li et al. 2022). PFOA and PFOS may be successfully oxidized in an electrochemical manner by boron-doped diamond (BDD) anodes, with direct anodic oxidation being the predominant mechanism (Zhuo et al. 2020). However, these studies were carried out in synthetic supporting electrolyte solutions with high or low conductivity, but high initial PFASs concentrations. Nevertheless, concentrations of PFASs are relatively low and rarely exceed 1 μg/L (Table 3.1).

Obviously, the treatment of PFASs from water using a combination of electrochemical oxidation and advanced oxidation is more effective (Wang et al. 2020a; Zhou et al. 2021). The electrode materials, on the other hand, remain a source of worry due to their high cost, limited activity, and short service life. In addition, all of the investigations relied on a reasonably pure reaction system (carried out with deionized water spiked with chosen PFASs) and were still in the theoretical/lab experimental stage.

3.3.3.4 Biodegradation

The most reliable and cost-effectiveness approach for wastewater treatment is bioremediation process. However, WWTPs are an important point source of PFASs. The fluorine-saturated carbon chain element structure of PFASs impeded the oxidative degradation of microorganisms (Lenka et al. 2021). Therefore, it is difficult for microorganisms to use such substances as carbon sources and energy sources.

PFASs precursors have carbon–hydrogen (C–H) and carbon–oxygen (C–O) bonds, as well as carbon–nitrogen (C–N) bonds in their molecular structure, which may convert precursor organics to PFAAs via microbial reactions (Yin et al. 2019, 2018). However, according to several studies (Huang and Jaffé 2019; Yu et al. 2020, 2022), PFASs are difficult to entirely decompose by a single biodegradation pathway.

Although a few studies reported some special microbial degradation of PFOA/PFOS, these studies were almost all long-term microbial degradation under special pure bacterial culture and sensitive to environmental changes as well as no complete mineralization (Zhang et al. 2022; Huang and Jaffé 2019; Ruiz-Urigüen et al. 2022). For example, *Acidimicrobium* sp. strain A6 is selected and employed for PFASs biodegradation with the average 77% decrease in PFOA concentration under 18 days of operation (Ruiz-Urigüen et al. 2022). Obviously, more work is highly desirable with the aim to improve the microbial biodegradation ability of PFASs.

Overall, most degradation technologies' energy costs constrain their long-term sustainability and acceptability, while the formation of hazardous by-products (e.g., short-chain PFAAs, bromate, and perchlorate) remains a problem. Each single treatment technique has its advantage and disadvantage (Table 3.3), so combination of different treatment techniques is often the best solution for control PFASs from water.

3.4 Potential Approach of CW-MFC

Many POPs and CECs, such as antibiotics, pharmaceutical and personal care products (PPCP), as well as insecticides, could be effectively removed in CW systems (Vymazal and Březinová 2015; Brunhoferova et al. 2021; Liu et al. 2019). Substrate serves as an adsorbent, a media for wetland plant growth, and a carrier for biofilm formation, among other components to play a key role in CW system. Various wetland substrates (GAC, zeolite, and biochar) are also used for the adsorption removal of PFASs from water (Du et al. 2014). With enough adsorbent amount and adsorption capability in the wetland substrate, both conventional pollutants and trace PFASs should be removed concurrently. There is no doubt that the use of appropriate adsorbents in the construction of CW filler beds can provide long-term effective adsorption of long-chain and/or short-chain PFASs on the field scale.

Plants are another key component of wetlands. They can uptake and accumulate PFASs in a variety of environments and applications, including laboratory experiments (Knight et al. 2021; Krippner et al. 2015; Zhang and Liang 2020; Zhou et al. 2019) and field surveys (Yamazaki et al. 2019). Because of worries about PFASs traveling via animals or crops and into humans, most previous research focused on irrigated crops in PFASs-contaminated soil or water (Zhou et al. 2019; Brown et al. 2020; Miranda et al. 2021). Several studies have found that wetland plants have potential ability for accumulating PFASs, with significant levels of PFASs found in plant tissues such as root, straw, and grains (Wang et al. 2020b; Yin et al. 2017). Short-chain PFCAs have a higher bioaccumulation potential in plant leaves than long-chain PFCAs with a low octanol/water partition coefficient (K_{ow}). For long-chain PFCAs, however, root concentration factors (RCF) rose with chain length (Lesmeister et al. 2021; Mei et al. 2021). Because of their hydrophilicity and mobility, short-chain PFASs are more likely to be uptaken and bioaccumulated in plant above-ground components. More importantly, it may be anticipated that by rationally structuring wetland substrates and plants, various components of CW could work together to remove various kinds of PFASs. Wetland plants for PFASs removal must be carefully chosen since they are a significant aspect of the biological habitat. To avoid being eaten by other organisms (animals, insects), it is advised to choose fern plants. It should be highlighted that when PFASs have been removed, disposing and regenerating the plants and substrate used in CW remain a significant challenge. The use of destructive treatment technique to achieve mineralization of PFASs is a viable option.

On the other hand, although biological approaches to the treatment of PFASs are extremely limited and not currently considered feasible, CW-MFC system provides a potential bioremediation approach. Due to unique electroactive bacteria around

Table 3.3 Advantages and disadvantages of various existing technologies for remove PFASs from water (Ji et al. 2020)

Technology	Application media	Scale	Advantages	Disadvantages
Adsorption	Wastewater Surface water Drinking water	Full-scale	• Easy to operate • Tailor-made of adsorbents • Good removal of several long-chain PFASs	• Poor in clearing short-chain PFASs • Unable to remove trace level of PFASs • Difficulty regeneration • Impact with other pollutants
Membrane filtration	Wastewater Surface water Drinking water	Field pilot	• Good performance • Wide range of application scenarios	• High-operating costs • Based on the PFASs' molecular weight • High concentrations of residues
Advanced oxidation & reduction	Wastewater Surface water	Field pilot	• Able to mineralize PFASs • Quicker reaction capability	• Require extreme operating conditions, centralized equipment, and massive chemical • Poor in treating some PFASs • Forming intermediate product • Impact with other pollutants
Thermal treatment	Wastewater	Lab-scale	• Able to mineralize PFASs	• Required at high temperatures • May form a potential source of air pollution
Electrochemical	Wastewater Surface water Drinking water	Field pilot	• Able to mineralize PFASs • Could be used in combination with other treatment methods	• High-energy • High-operating costs • Poor in treating some PFASs • Forming intermediate product
Bioremediation	Surface water	Lab-scale	• Cost-efficiency • Green solution	• Few evidences could completely degrade PFASs • Requires specific environmental

anode chamber, CW-MFC has been investigated in recent years to remove a variety of biorefractory organic contaminants. CW-MFC could effectively treat wastewater with high antibiotic and PPCPs (Wang et al. 2020c; Zhang et al. 2017a, b). Biodegradation, substrate absorption, and plant uptake were found to have distinct roles in removing pollutants in these studies, notably biodegradation, and plant uptake. It has been demonstrated that a bioelectrochemical system not only creates a battery circuit that can promote microbial metabolism but also selectively enriches electrochemically active microbial communities for refractory organics (Li et al. 2019b; Wen et al. 2022; Xu et al. 2019).

The accumulation of PFASs in the substrate with long hydraulic retention time, and bioelectrochemical stimulation in CW-MFC offers a favored condition for incubation and/or domestication PFASs-degrading microorganisms. Moreover, there are few studies, showing that the special microbial can degrade of PFOA in lab experiment (Sect. 3.3.4). It seems that there is a condition and pathway for PFOA biodegradation or biotransformation due to the abundant microbial population and suitable microenvironment in CW-MFC system. However, further studies are highly desirable.

Based on the above clues, using CW-MFC to removal PFASs in water was proposed by Ji et al. (2020) (Fig. 3.2). Subsequently, related experiments were carried out, while the results showed that when the concentrations of PFOA and PFOS in the influent were 6.46 ± 0.52 μg/L and 9.34 ± 0.87 μg/L, respectively, both closed-circuit and open-circuit operations of the CW-MFC systems demonstrated over 96% removal performance of PFASs (Ji 2022). These results indicate that the CW-MFC system can effectively remove PFASs from wastewater.

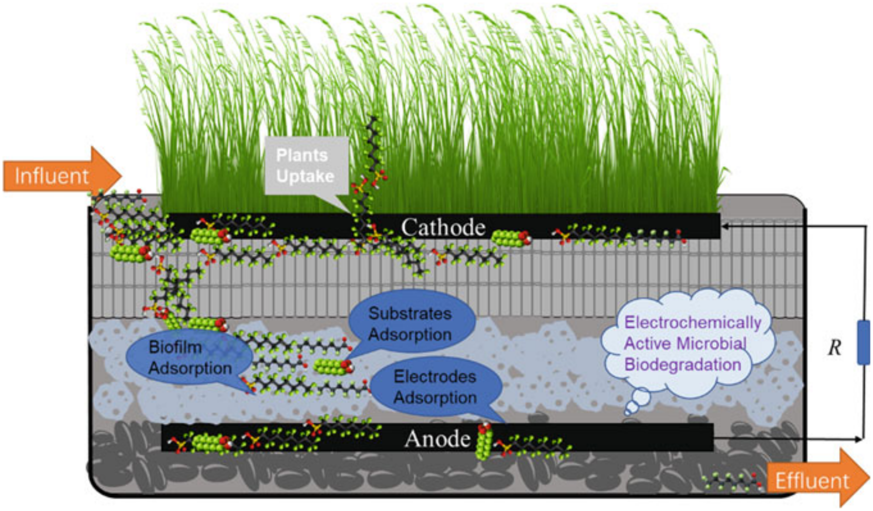

Fig. 3.2 Principle of PFASs removal in proposed CW-MFC system

3.5 Conclusion

The current review provides a brief overview of the occurrence and properties of PFASs in water environment, with an emphasis on problems and feasible removal solutions based on published literature. Some physical, chemical, and limited biodegradation methods have been documented to degrade or transfer PFASs to some extent. However, these methods are insufficiently thorough and not environmentally friendly. Given the fact that PFASs are very stable compounds with distinct physicochemical features, the integration approach or a combined system may be a viable option for PFASs control. CW-MFC system could provide an integrated and environmentally friendly while sustainable way to remove PFASs from water through substrate adsorption, plant uptake, and enhanced biodegradation.

References

Ahmed MB, Alam MdM, Zhou JL, Xu B, Johir MAH, Karmakar AK, Rahman MdS, Hossen J, Hasan ATMK, Moni MA (2020) Advanced treatment technologies efficacies and mechanism of per- and poly-fluoroalkyl substances removal from water. Process Saf Environ Prot 136:1–14. https://doi.org/10.1016/j.psep.2020.01.005

An W, Duan L, Zhang Y, Wang B, Liu CS, Wang F, Sui Q, Xu D, Yu G (2021) Occurrence, spatiotemporal distribution, seasonal and annual variation, and source apportionment of poly- and perfluoroalkyl substances (PFASs) in the northwest of Tai Lake Basin, China. J Hazard Mater 416:125784. https://doi.org/10.1016/j.jhazmat.2021.125784

Anumol T, Dagnino S, Vandervort DR, Snyder SA (2016) Transformation of Polyfluorinated compounds in natural waters by advanced oxidation processes. Chemosphere 144:1780–1787. https://doi.org/10.1016/j.chemosphere.2015.10.070

Arvaniti OS, Hwang Y, Andersen HR, Stasinakis AS, Thomaidis NS, Aloupi M (2015) Reductive degradation of perfluorinated compounds in water using Mg-aminoclay coated nanoscale zero valent iron. Chem Eng J 262:133–139. https://doi.org/10.1016/j.cej.2014.09.079

Australian Government PFAS Taskforce. https://www.pfas.gov.au/government-action/pfas-food-water. Last accessed 11 Sept 2022

Bai L, Jiang Y, Xia D, Wei Z, Spinney R, Dionysiou DD, Minakata D, Xiao R, Xie H-B, Chai L (2022) Mechanistic understanding of superoxide radical-mediated degradation of perfluorocarboxylic acids. Environ Sci Technol 56:624–633. https://doi.org/10.1021/acs.est.1c06356

Belkouteb N, Franke V, McCleaf P, Köhler S, Ahrens L (2020) Removal of per- and polyfluoroalkyl substances (PFASs) in a full-scale drinking water treatment plant: long-term performance of granular activated carbon (GAC) and influence of flow-rate. Water Res 182:115913. https://doi.org/10.1016/j.watres.2020.115913

Brown JB, Conder JM, Arblaster JA, Higgins CP (2020) Assessing human health risks from per- and polyfluoroalkyl substance (PFAS)-impacted vegetable consumption: a tiered modeling approach. Environ Sci Technol 54:15202–15214. https://doi.org/10.1021/acs.est.0c03411

Brunhoferova H, Venditti S, Schlienz M, Hansen J (2021) Removal of 27 micropollutants by selected wetland macrophytes in hydroponic conditions. Chemosphere 281:130980. https://doi.org/10.1016/j.chemosphere.2021.130980

Buck RC, Franklin J, Berger U, Conder JM, Cousins IT, de Voogt P, Jensen AA, Kannan K, Mabury SA, van Leeuwen SP (2011) Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. Integr Environ Assess Manag 7:513–541. https://doi.org/10.1002/ieam.258

Cai Y, Chen H, Yuan R, Wang F, Chen Z, Zhou B (2019) Toxicity of perfluorinated compounds to soil microbial activity: effect of carbon chain length, functional group and soil properties. Sci Total Environ 690:1162–1169. https://doi.org/10.1016/j.scitotenv.2019.06.440

Cai L, Hu J, Li J, Cao X, Lyu Y, Sun W (2022) Occurrence, source apportionment, and pollution assessment of per- and polyfluoroalkyl substances in a river across rural and urban areas. Sci Total Environ 835:155505. https://doi.org/10.1016/j.scitotenv.2022.155505

Cao H, Zhang W, Wang C, Liang Y (2020) Sonochemical degradation of poly- and perfluoroalkyl substances—a review. Ultrason Sonochem 69:105245. https://doi.org/10.1016/j.ultsonch.2020.105245

Chen R, Li G, Yu Y, Ma X, Zhuang Y, Tao H, Shi B (2019a) Occurrence and transport behaviors of perfluoroalkyl acids in drinking water distribution systems. Sci Total Environ 697:134162. https://doi.org/10.1016/j.scitotenv.2019.134162

Chen Z, Tian H, Li H, Li J, Hong R, Sheng F, Wang C, Gu C (2019b) Application of surfactant modified montmorillonite with different conformation for photo-treatment of perfluorooctanoic acid by hydrated electrons. Chemosphere 235:1180–1188. https://doi.org/10.1016/j.chemosphere.2019.07.032

Chen Z, Li C, Gao J, Dong H, Chen Y, Wu B, Gu C (2020) Efficient reductive destruction of perfluoroalkyl substances under self-assembled micelle confinement. Environ Sci Technol 54:5178–5185. https://doi.org/10.1021/acs.est.9b06599

China Standardization Administration. https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=99E9C17E3547A3C0CE2FD1FFD9F2F7BE. Last accessed 11 Sept 2022

Ching C, Ling Y, Trang B, Klemes M, Xiao L, Yang A, Barin G, Dichtel WR, Helbling DE (2022) Identifying the physicochemical properties of β-cyclodextrin polymers that determine the adsorption of perfluoroalkyl acids. Water Res 209:117938. https://doi.org/10.1016/j.watres.2021.117938

Chow SJ, Ojeda N, Jacangelo JG, Schwab KJ (2021) Detection of ultrashort-chain and other per- and polyfluoroalkyl substances (PFAS) in U.S. bottled water. Water Res 201:117292. https://doi.org/10.1016/j.watres.2021.117292

Coggan TL, Moodie D, Kolobaric A, Szabo D, Shimeta J, Crosbie ND, Lee E, Fernandes M, Clarke BO (2019) An investigation into per- and polyfluoroalkyl substances (PFAS) in nineteen Australian wastewater treatment plants (WWTPs). Heliyon 5:e02316. https://doi.org/10.1016/j.heliyon.2019.e02316

Cordner A, Goldenman G, Birnbaum LS, Brown P, Miller MF, Mueller R, Patton S, Salvatore DH, Trasande L (2021) The true cost of PFAS and the benefits of acting now. Environ Sci Technol 55:9630–9633. https://doi.org/10.1021/acs.est.1c03565

Danish EPA. https://www2.mst.dk/Udgiv/publications/2015/04/978-87-93283-01-5.pdf. Last accessed 11 Sept 2022

De Silva AO, Armitage JM, Bruton TA, Dassuncao C, Heiger-Bernays W, Hu XC, Kärrman A, Kelly B, Ng C, Robuck A, Sun M, Webster TF, Sunderland EM (2021) PFAS exposure pathways for humans and wildlife: a synthesis of current knowledge and key gaps in understanding. Environ Toxicol Chem 40:631–657. https://doi.org/10.1002/etc.4935

Dong H, Lu G, Yan Z, Liu J, Yang H, Zhang P, Jiang R, Bao X, Nkoom M (2020) Distribution, sources and human risk of perfluoroalkyl acids (PFAAs) in a receiving riverine environment of the Nanjing urban area, East China. J Hazard Mater 381:120911. https://doi.org/10.1016/j.jhazmat.2019.120911

Du Z, Deng S, Bei Y, Huang Q, Wang B, Huang J, Yu G (2014) Adsorption behavior and mechanism of perfluorinated compounds on various adsorbents—a review. J Hazard Mater 274:443–454. https://doi.org/10.1016/j.jhazmat.2014.04.038

Gao Y, Liang Y, Gao K, Wang Y, Wang C, Fu J, Wang Y, Jiang G, Jiang Y (2019) Levels, spatial distribution and isomer profiles of perfluoroalkyl acids in soil, groundwater and tap water around a manufactory in China. Chemosphere 227:305–314. https://doi.org/10.1016/j.chemosphere.2019.04.027

Gomez-Ruiz B, Gómez-Lavín S, Diban N, Boiteux V, Colin A, Dauchy X, Urtiaga A (2017) Efficient electrochemical degradation of poly- and perfluoroalkyl substances (PFASs) from the effluents of an industrial wastewater treatment plant. Chem Eng J 322:196–204. https://doi.org/10.1016/j.cej.2017.04.040

Hao S, Choi YJ, Deeb RA, Strathmann TJ, Higgins CP (2022) Application of hydrothermal alkaline treatment for destruction of per- and polyfluoroalkyl substances in contaminated groundwater and soil. Environ Sci Technol 56:6647–6657. https://doi.org/10.1021/acs.est.2c00654

Harrad S, Wemken N, Drage DS, Abdallah MA-E, Coggins A-M (2019) Perfluoroalkyl substances in drinking water, indoor air and dust from Ireland: implications for human exposure. Environ Sci Technol 53:13449–13457. https://doi.org/10.1021/acs.est.9b04604

Health Canada. https://www.canada.ca/en/health-canada/programs/consultation-perfluorooctanoic-acid-pfoa-in-drinking-water/document.html. Last accessed 11 Sept 2022

Hori H, Nagaoka Y, Sano T, Kutsuna S (2008) Iron-induced decomposition of perfluorohexanesulfonate in sub- and supercritical water. Chemosphere 70:800–806. https://doi.org/10.1016/j.chemosphere.2007.07.015

Huang S, Jaffé PR (2019) Defluorination of perfluorooctanoic Acid (PFOA) and perfluorooctane sulfonate (PFOS) by *Acidimicrobium* sp. Strain A6. Environ Sci Technol 53:11410–11419. https://doi.org/10.1021/acs.est.9b04047

JDSUPRA. https://www.jdsupra.com/legalnews/pfas-update-state-by-state-regulation-4639985/. Last accessed 11 Sept 2022

Ji B, Kang P, Wei T, Zhao Y (2020) Challenges of aqueous per- and polyfluoroalkyl substances (PFASs) and their foreseeable removal strategies. Chemosphere 250:126316. https://doi.org/10.1016/j.chemosphere.2020.126316

Ji B (2022) Insight into the constructed wetland-microbial fuel cell technology: electrode materials, plant cultivation, and PFASs exposure. Ph.D. Thesis, Xi'an University of Technology

Jiang J-J, Okvitasari AR, Huang F-Y, Tsai C-S (2021) Characteristics, pollution patterns and risks of perfluoroalkyl substances in drinking water sources of Taiwan. Chemosphere 264:128579. https://doi.org/10.1016/j.chemosphere.2020.128579

Jin L, Zhang P, Shao T, Zhao S (2014) Ferric ion mediated photodecomposition of aqueous perfluorooctane sulfonate (PFOS) under UV irradiation and its mechanism. J Hazard Mater 271:9–15. https://doi.org/10.1016/j.jhazmat.2014.01.061

Khan MY, So S, da Silva G (2020) Decomposition kinetics of perfluorinated sulfonic acids. Chemosphere 238:124615. https://doi.org/10.1016/j.chemosphere.2019.124615

Knight ER, Bräunig J, Janik LJ, Navarro DA, Kookana RS, Mueller JF, McLaughlin MJ (2021) An investigation into the long-term binding and uptake of PFOS, PFOA and PFHxS in soil–plant systems. J Hazard Mater 404:124065. https://doi.org/10.1016/j.jhazmat.2020.124065

Krippner J, Falk S, Brunn H, Georgii S, Schubert S, Stahl T (2015) Accumulation potentials of perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) in maize (*Zea mays*). J Agric Food Chem 63:3646–3653. https://doi.org/10.1021/acs.jafc.5b00012

Kurwadkar S, Dane J, Kanel SR, Nadagouda MN, Cawdrey RW, Ambade B, Struckhoff GC, Wilkin R (2022) Per- and polyfluoroalkyl substances in water and wastewater: a critical review of their global occurrence and distribution. Sci Total Environ 809:151003. https://doi.org/10.1016/j.scitotenv.2021.151003

Lee Y-M, Lee J-Y, Kim M-K, Yang H, Lee J-E, Son Y, Kho Y, Choi K, Zoh K-D (2020) Concentration and distribution of per- and polyfluoroalkyl substances (PFAS) in the Asan Lake area of South Korea. J Hazard Mater 381:120909. https://doi.org/10.1016/j.jhazmat.2019.120909

Lei Y-J, Tian Y, Sobhani Z, Naidu R, Fang C (2020) Synergistic degradation of PFAS in water and soil by dual-frequency ultrasonic activated persulfate. Chem Eng J 388:124215. https://doi.org/10.1016/j.cej.2020.124215

Léniz-Pizarro F, Vogler RJ, Sandman P, Harris N, Ormsbee LE, Liu C, Bhattacharyya D (2022) Dual-functional nanofiltration and adsorptive membranes for PFAS and organics separation from water. ACS EST Water 2:863–872. https://doi.org/10.1021/acsestwater.2c00043

Lenka SP, Kah M, Padhye LP (2021) A review of the occurrence, transformation, and removal of poly- and perfluoroalkyl substances (PFAS) in wastewater treatment plants. Water Res 199:117187. https://doi.org/10.1016/j.watres.2021.117187

Lesmeister L, Lange FT, Breuer J, Biegel-Engler A, Giese E, Scheurer M (2021) Extending the knowledge about PFAS bioaccumulation factors for agricultural plants—a review. Sci Total Environ 766:142640. https://doi.org/10.1016/j.scitotenv.2020.142640

Li Y, Zhu G, Ng WJ, Tan SK (2014) A review on removing pharmaceutical contaminants from wastewater by constructed wetlands: design, performance and mechanism. Sci Total Environ 468–469:908–932. https://doi.org/10.1016/j.scitotenv.2013.09.018

Li M, Sun F, Shang W, Zhang X, Dong W, Liu T, Pang W (2019a) Theoretical studies of perfluorochemicals (PFCs) adsorption mechanism on the carbonaceous surface. Chemosphere 235:606–615. https://doi.org/10.1016/j.chemosphere.2019.06.191

Li H, Zhang S, Yang X-L, Yang Y-L, Xu H, Li X-N, Song H-L (2019b) Enhanced degradation of bisphenol A and ibuprofen by an up-flow microbial fuel cell-coupled constructed wetland and analysis of bacterial community structure. Chemosphere 217:599–608. https://doi.org/10.1016/j.chemosphere.2018.11.022

Li M, Jin Y-T, Yan J-F, Liu Z, Feng N-X, Han W, Huang L-W, Li Q-K, Yeung K-L, Zhou S-Q, Mo C-H (2022) Exploration of perfluorooctane sulfonate degradation properties and mechanism via electron-transfer dominated radical process. Water Res 215:118259. https://doi.org/10.1016/j.watres.2022.118259

Liu Y, Hu X-M, Zhao Y, Wang J, Lu M-X, Peng F-H, Bao J (2018) Removal of perfluorooctanoic acid in simulated and natural waters with different electrode materials by electrocoagulation. Chemosphere 201:303–309. https://doi.org/10.1016/j.chemosphere.2018.02.129

Liu T, Xu S, Lu S, Qin P, Bi B, Ding H, Liu Y, Guo X, Liu X (2019) A review on removal of organophosphorus pesticides in constructed wetland: performance, mechanism and influencing factors. Sci Total Environ 651:2247–2268. https://doi.org/10.1016/j.scitotenv.2018.10.087

Liu S, Jin B, Arp HPH, Chen W, Liu Y, Zhang G (2022) The fate and transport of chlorinated polyfluorinated ether sulfonates and other PFAS through industrial wastewater treatment facilities in China. Environ Sci Technol 56:3002–3010. https://doi.org/10.1021/acs.est.1c04276

Lu D, Sha S, Luo J, Huang Z, Zhang Jackie X (2020) Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): a critical review. J Hazard Mater 386:121963. https://doi.org/10.1016/j.jhazmat.2019.121963

Lu Y, Gao J, Nguyen HT, Vijayasarathy S, Du P, Li X, Yao H, Mueller JF, Thai PK (2021) Occurrence of per- and polyfluoroalkyl substances (PFASs) in wastewater of major cities across China in 2014 and 2016. Chemosphere 279:130590. https://doi.org/10.1016/j.chemosphere.2021.130590

Macorps N, Le Menach K, Pardon P, Guérin-Rechdaoui S, Rocher V, Budzinski H, Labadie P (2022) Bioaccumulation of per- and polyfluoroalkyl substance in fish from an urban river: occurrence, patterns and investigation of potential ecological drivers. Environ Pollut 303:119165. https://doi.org/10.1016/j.envpol.2022.119165

Masoner JR, Kolpin DW, Cozzarelli IM, Smalling KL, Bolyard SC, Field JA, Furlong ET, Gray JL, Lozinski D, Reinhart D, Rodowa A, Bradley PM (2020) Landfill leachate contributes per-/poly-fluoroalkyl substances (PFAS) and pharmaceuticals to municipal wastewater. Environ Sci Water Res Technol 6:1300–1311. https://doi.org/10.1039/D0EW00045K

Mastropietro TF, Bruno R, Pardo E, Armentano D (2021) Reverse osmosis and nanofiltration membranes for highly efficient PFASs removal: overview, challenges and future perspectives. Dalton Trans 50:5398–5410. https://doi.org/10.1039/D1DT00360G

Matamoros V, García J, Bayona JM (2008) Organic micropollutant removal in a full-scale surface flow constructed wetland fed with secondary effluent. Water Res 42:653–660. https://doi.org/10.1016/j.watres.2007.08.016

McCleaf P, Englund S, Östlund A, Lindegren K, Wiberg K, Ahrens L (2017) Removal efficiency of multiple poly- and perfluoroalkyl substances (PFASs) in drinking water using granular activated carbon (GAC) and anion exchange (AE) column tests. Water Res 120:77–87. https://doi.org/10.1016/j.watres.2017.04.057

Mei W, Sun H, Song M, Jiang L, Li Y, Lu W, Ying G-G, Luo C, Zhang G (2021) Per- and polyfluoroalkyl substances (PFASs) in the soil–plant system: sorption, root uptake, and translocation. Environ Int 156:106642. https://doi.org/10.1016/j.envint.2021.106642

Miranda DA, Benskin JP, Awad R, Lepoint G, Leonel J, Hatje V (2021) Bioaccumulation of per- and polyfluoroalkyl substances (PFASs) in a tropical estuarine food web. Sci Total Environ 754:142146. https://doi.org/10.1016/j.scitotenv.2020.142146

Mu T, Park M, Kim K-Y (2021) Energy-efficient removal of PFOA and PFOS in water using electrocoagulation with an air-cathode. Chemosphere 281:130956. https://doi.org/10.1016/j.chemosphere.2021.130956

Naidu R, Nadebaum P, Fang C, Cousins I, Pennell K, Conder J, Newell CJ, Longpré D, Warner S, Crosbie ND, Surapaneni A, Bekele D, Spiese R, Bradshaw T, Slee D, Liu Y, Qi F, Mallavarapu M, Duan L, McLeod L, Bowman M, Richmond B, Srivastava P, Chadalavada S, Umeh A, Biswas B, Barclay A, Simon J, Nathanail P (2020) Per- and poly-fluoroalkyl substances (PFAS): current status and research needs. Environ Technol Innov 19:100915. https://doi.org/10.1016/j.eti.2020.100915

Niu J, Li Y, Shang E, Xu Z, Liu J (2016) Electrochemical oxidation of perfluorinated compounds in water. Chemosphere 146:526–538. https://doi.org/10.1016/j.chemosphere.2015.11.115

Oliver DP, Li Y, Orr R, Nelson P, Barnes M, McLaughlin MJ, Kookana RS (2019) The role of surface charge and pH changes in tropical soils on sorption behaviour of per- and polyfluoroalkyl substances (PFASs). Sci Total Environ 673:197–206. https://doi.org/10.1016/j.scitotenv.2019.04.055

Olsen GW, Burris JM, Ehresman DJ, Froehlich JW, Seacat AM, Butenhoff JL, Zobel LR (2007) Half-life of serum elimination of perfluorooctanesulfonate, perfluorohexanesulfonate, and perfluorooctanoate in retired fluorochemical production workers. Environ Health Perspect 115(9):1298–1305. https://doi.org/10.1289/ehp.10009

Oyetade OA, Varadwaj GBB, Nyamori VO, Jonnalagadda SB, Martincigh BS (2018) A critical review of the occurrence of perfluoroalkyl acids in aqueous environments and their removal by adsorption onto carbon nanotubes. Rev Environ Sci Biotechnol 17:603–635. https://doi.org/10.1007/s11157-018-9479-9

Pauletto PS, Bandosz TJ (2022) Activated carbon versus metal-organic frameworks: a review of their PFAS adsorption performance. J Hazard Mater 425:127810. https://doi.org/10.1016/j.jhazmat.2021.127810

Pistocchi A, Loos R (2009) A Map of European emissions and concentrations of PFOS and PFOA. Environ Sci Technol 43:9237–9244. https://doi.org/10.1021/es901246d

Podder A, Sadmani AHMA, Reinhart D, Chang N-B, Goel R (2021) Per and poly-fluoroalkyl substances (PFAS) as a contaminant of emerging concern in surface water: a transboundary review of their occurrences and toxicity effects. J Hazard Mater 419:126361. https://doi.org/10.1016/j.jhazmat.2021.126361

Qi Y, Cao H, Pan W, Wang C, Liang Y (2022) The role of dissolved organic matter during per- and polyfluorinated substance (PFAS) adsorption, degradation, and plant uptake: a review. J Hazard Mater 436:129139. https://doi.org/10.1016/j.jhazmat.2022.129139

Qian L, Kopinke F-D, Georgi A (2021) Photodegradation of perfluorooctanesulfonic acid on Fe-zeolites in water. Environ Sci Technol 55:614–622. https://doi.org/10.1021/acs.est.0c04558

Qu Y, Huang J, Willand W, Weber R (2020) Occurrence, removal and emission of per- and polyfluorinated alkyl substances (PFASs) from chrome plating industry: a case study in Southeast China. Emerg Contam 6:376–384. https://doi.org/10.1016/j.emcon.2020.10.001

Rodriguez-Freire L, Balachandran R, Sierra-Alvarez R, Keswani M (2015) Effect of sound frequency and initial concentration on the sonochemical degradation of perfluorooctane sulfonate (PFOS). J Hazard Mater 300:662–669. https://doi.org/10.1016/j.jhazmat.2015.07.077

Ross I, McDonough J, Miles J, Storch P, Thelakkat Kochunarayanan P, Kalve E, Hurst J, Dasgupta S, Burdick J (2018) A review of emerging technologies for remediation of PFASs. Remediat J 28:101–126. https://doi.org/10.1002/rem.21553

Ruiz-Urigüen M, Shuai W, Huang S, Jaffé PR (2022) Biodegradation of PFOA in microbial electrolysis cells by *Acidimicrobiaceae* sp. strain A6. Chemosphere 292:133506. https://doi.org/10.1016/j.chemosphere.2021.133506

Santos A, Rodríguez S, Pardo F, Romero A (2016) Use of Fenton reagent combined with humic acids for the removal of PFOA from contaminated water. Sci Total Environ 563–564:657–663. https://doi.org/10.1016/j.scitotenv.2015.09.044

Sinclair GM, Long SM, Jones OAH (2020) What are the effects of PFAS exposure at environmentally relevant concentrations? Chemosphere 258:127340. https://doi.org/10.1016/j.chemosphere.2020.127340

Sørmo E, Silvani L, Bjerkli N, Hagemann N, Zimmerman AR, Hale SE, Hansen CB, Hartnik T, Cornelissen G (2021) Stabilization of PFAS-contaminated soil with activated biochar. Sci Total Environ 763:144034. https://doi.org/10.1016/j.scitotenv.2020.144034

Sunderland EM, Hu XC, Dassuncao C, Tokranov AK, Wagner CC, Allen JG (2019) A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. J Expo Sci Environ Epidemiol 29(2):131–147. https://doi.org/10.1038/s41370-018-0094-1

Szabo D, Coggan TL, Robson TC, Currell M, Clarke BO (2018) Investigating recycled water use as a diffuse source of per- and polyfluoroalkyl substances (PFASs) to groundwater in Melbourne, Australia. Sci Total Environ 644:1409–1417. https://doi.org/10.1016/j.scitotenv.2018.07.048

Tang CY, Fu QS, Criddle CS, Leckie JO (2007) Effect of flux (transmembrane pressure) and membrane properties on fouling and rejection of reverse osmosis and nanofiltration membranes treating perfluorooctane sulfonate containing wastewater. Environ Sci Technol 41:2008–2014. https://doi.org/10.1021/es062052f

Teymourian T, Teymoorian T, Kowsari E, Ramakrishna S (2021) A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism. Res Chem Intermed 47:4879–4914. https://doi.org/10.1007/s11164-021-04603-7

UKDWI. https://www.dwi.gov.uk/en/private-water-supplies/pws-installations/guidance-on-the-water-supply-water-quality-regulations-2016-specific-to-pfos-perfluorooctane-sulphonate-and-pfoa-perfluorooctanoic-acid-concentrations-in-drinking-water/. Last accessed 11 Sept 2022

USEPA. https://www.epa.gov/sdwa/drinking-water-health-advisories-pfoa-and-pfos. Last accessed 11 Sept 2022

Vymazal J, Březinová T (2015) The use of constructed wetlands for removal of pesticides from agricultural runoff and drainage: a review. Environ Int 75:11–20. https://doi.org/10.1016/j.envint.2014.10.026

Wang F, Liu C, Shih K (2012) Adsorption behavior of perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA) on boehmite. Chemosphere 89:1009–1014. https://doi.org/10.1016/j.chemosphere.2012.06.071

Wang J, Wang L, Xu C, Zhi R, Miao R, Liang T, Yue X, Lv Y, Liu T (2018) Perfluorooctane sulfonate and perfluorobutane sulfonate removal from water by nanofiltration membrane: the roles of solute concentration, ionic strength, and macromolecular organic foulants. Chem Eng J 332:787–797. https://doi.org/10.1016/j.cej.2017.09.061

Wang J, Song X, Li Q, Bai H, Zhu C, Weng B, Yan D, Bai J (2019a) Bioenergy generation and degradation pathway of phenanthrene and anthracene in a constructed wetland-microbial fuel cell with an anode amended with nZVI. Water Res 150:340–348. https://doi.org/10.1016/j.watres.2018.11.075

Wang Q, Tsui MMP, Ruan Y, Lin H, Zhao Z, Ku JPH, Sun H, Lam PKS (2019b) Occurrence and distribution of per- and polyfluoroalkyl substances (PFASs) in the seawater and sediment of the South China Sea coastal region. Chemosphere 231:468–477. https://doi.org/10.1016/j.chemosphere.2019.05.162

Wang K, Huang D, Wang W, Ji Y, Niu J (2020a) Enhanced perfluorooctanoic acid degradation by electrochemical activation of peroxymonosulfate in aqueous solution. Environ Int 137:105562. https://doi.org/10.1016/j.envint.2020.105562

Wang T-T, Ying G-G, Shi W-J, Zhao J-L, Liu Y-S, Chen J, Ma D-D, Xiong Q (2020b) Uptake and translocation of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) by wetland plants: tissue- and cell-level distribution visualization with desorption electrospray ionization mass spectrometry (DESI-MS) and transmission electron microscopy equipped with energy-dispersive spectroscopy (TEM-EDS). Environ Sci Technol 54:6009–6020. https://doi.org/10.1021/acs.est.9b05160

Wang Q, Lv R, Rene ER, Qi X, Hao Q, Du Y, Zhao C, Xu F, Kong Q (2020c) Characterization of microbial community and resistance gene (CzcA) shifts in up-flow constructed wetlands-microbial fuel cell treating Zn (II) contaminated wastewater. Bioresour Technol 302:122867. https://doi.org/10.1016/j.biortech.2020.122867

Wang Z, Buser AM, Cousins IT, Demattio S, Drost W, Johansson O, Ohno K, Patlewicz G, Richard AM, Walker GW, White GS, Leinala E (2021) A new OECD definition for per- and polyfluoroalkyl substances. Environ Sci Technol 55(23):15575–15578. https://doi.org/10.1021/acs.est.1c06896

Wen H, Zhu H, Yan B, Bañuelos G, Shutes B, Wang X, Cao S, Cheng R, Tian L (2022) High removal efficiencies of antibiotics and low accumulation of antibiotic resistant genes obtained in microbial fuel cell-constructed wetlands intensified by sponge iron. Sci Total Environ 806:150220. https://doi.org/10.1016/j.scitotenv.2021.150220

Wu D, Li X, Zhang J, Chen W, Lu P, Tang Y, Li L (2018) Efficient PFOA degradation by persulfate-assisted photocatalytic ozonation. Sep Purif Technol 207:255–261. https://doi.org/10.1016/j.seppur.2018.06.059

Wu B, Hao S, Choi Y, Higgins CP, Deeb R, Strathmann TJ (2019) Rapid destruction and defluorination of perfluorooctanesulfonate by alkaline hydrothermal reaction. Environ Sci Technol Lett 6:630–636. https://doi.org/10.1021/acs.estlett.9b00506

Xiao X, Ulrich BA, Chen B, Higgins CP (2017) Sorption of poly- and perfluoroalkyl substances (PFASs) relevant to aqueous film-forming foam (AFFF)-impacted groundwater by biochars and activated carbon. Environ Sci Technol 51:6342–6351. https://doi.org/10.1021/acs.est.7b00970

Xiao S-K, Wu Q, Pan C-G, Yin C, Wang Y-H, Yu K-F (2021) Distribution, partitioning behavior and potential source of legacy and alternative per- and polyfluoroalkyl substances (PFASs) in water and sediments from a subtropical Gulf, South China Sea. Environ Res 201:111485. https://doi.org/10.1016/j.envres.2021.111485

Xiong J, Hou Y, Wang J, Liu Z, Qu Y, Li Z, Wang X (2021) The rejection of perfluoroalkyl substances by nanofiltration and reverse osmosis: influencing factors and combination processes. Environ Sci Water Res Technol. https://doi.org/10.1039/D1EW00490E

Xu P, Xiao E, Zeng L, He F, Wu Z (2019) Enhanced degradation of pyrene and phenanthrene in sediments through synergistic interactions between microbial fuel cells and submerged macrophyte *Vallisneria spiralis*. J Soils Sediments 19:2634–2649. https://doi.org/10.1007/s11368-019-02247-0

Yamazaki E, Taniyasu S, Ruan Y, Wang Q, Petrick G, Tanhua T, Gamo T, Wang X, Lam PKS, Yamashita N (2019) Vertical distribution of perfluoroalkyl substances in water columns around the Japan sea and the Mediterranean Sea. Chemosphere 231:487–494. https://doi.org/10.1016/j.chemosphere.2019.05.132

Yin T, Chen H, Reinhard M, Yi X, He Y, Gin KY-H (2017) Perfluoroalkyl and polyfluoroalkyl substances removal in a full-scale tropical constructed wetland system treating landfill leachate. Water Res 125:418–426. https://doi.org/10.1016/j.watres.2017.08.071

Yin T, Te SH, Reinhard M, Yang Y, Chen H, He Y, Gin KY-H (2018) Biotransformation of Sulfluramid (N-ethyl perfluorooctane sulfonamide) and dynamics of associated rhizospheric microbial community in microcosms of wetland plants. Chemosphere 211:379–389. https://doi.org/10.1016/j.chemosphere.2018.07.157

Yin T, Tran NH, Huiting C, He Y, Gin KY-H (2019) Biotransformation of polyfluoroalkyl substances by microbial consortia from constructed wetlands under aerobic and anoxic conditions. Chemosphere 233:101–109. https://doi.org/10.1016/j.chemosphere.2019.05.227

Yu Y, Zhang K, Li Z, Ren C, Chen J, Lin Y-H, Liu J, Men Y (2020) Microbial cleavage of C–F bonds in Two C_6 per- and polyfluorinated compounds via reductive defluorination. Environ Sci Technol 54:14393–14402. https://doi.org/10.1021/acs.est.0c04483

Yu Y, Che S, Ren C, Jin B, Tian Z, Liu J, Men Y (2022) Microbial defluorination of unsaturated per- and polyfluorinated carboxylic acids under anaerobic and aerobic conditions: a structure specificity study. Environ Sci Technol 56:4894–4904. https://doi.org/10.1021/acs.est.1c05509

Zhang W, Liang Y (2020) Removal of eight perfluoroalkyl acids from aqueous solutions by aeration and duckweed. Sci Total Environ 724:138357. https://doi.org/10.1016/j.scitotenv.2020.138357

Zhang S, Yang X-L, Li H, Song H-L, Wang R-C, Dai Z-Q (2017a) Degradation of sulfamethoxazole in bioelectrochemical system with power supplied by constructed wetland-coupled microbial fuel cells. Bioresour Technol 244:345–352. https://doi.org/10.1016/j.biortech.2017.07.143

Zhang S, Song H-L, Yang X-L, Huang S, Dai Z-Q, Li H, Zhang Y-Y (2017b) Dynamics of antibiotic resistance genes in microbial fuel cell-coupled constructed wetlands treating antibiotic-polluted water. Chemosphere 178:548–555. https://doi.org/10.1016/j.chemosphere.2017.03.088

Zhang S, Song H-L, Yang X-L, Li H, Wang Y-W (2018) A system composed of a biofilm electrode reactor and a microbial fuel cell-constructed wetland exhibited efficient sulfamethoxazole removal but induced sul genes. Bioresour Technol 256:224–231. https://doi.org/10.1016/j.biortech.2018.02.023

Zhang DQ, Zhang WL, Liang YN (2019a) Adsorption of perfluoroalkyl and polyfluoroalkyl substances (PFASs) from aqueous solution—a review. Sci Total Environ 694:133606. https://doi.org/10.1016/j.scitotenv.2019.133606

Zhang Y, Moores A, Liu J, Ghoshal S (2019b) New insights into the degradation mechanism of perfluorooctanoic acid by persulfate from density functional theory and experimental data. Environ Sci Technol 53:8672–8681. https://doi.org/10.1021/acs.est.9b00797

Zhang Z, Sarkar D, Datta R, Deng Y (2021) Adsorption of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) by aluminum-based drinking water treatment residuals. J Hazard Mater Lett 2:100034. https://doi.org/10.1016/j.hazl.2021.100034

Zhang Z, Sarkar D, Biswas JK, Datta R (2022) Biodegradation of per- and polyfluoroalkyl substances (PFAS): a review. Bioresour Technol 344:126223. https://doi.org/10.1016/j.biortech.2021.126223

Zhou Y, Lian Y, Sun X, Fu L, Duan S, Shang C, Jia X, Wu Y, Wang M (2019) Determination of 20 perfluoroalkyl substances in greenhouse vegetables with a modified one-step pretreatment approach coupled with ultra performance liquid chromatography tandem mass spectrometry (UPLC-MS-MS). Chemosphere 227:470–479. https://doi.org/10.1016/j.chemosphere.2019.04.034

Zhou Y, Lee Y, Ren Y, Cui M, Khim J (2021) Quantification of perfluorooctanoic acid decomposition mechanism applying negative voltage to anode during photoelectrochemical process. Chemosphere 284:131311. https://doi.org/10.1016/j.chemosphere.2021.131311

Zhuo Q, Wang J, Niu J, Yang B, Yang Y (2020) Electrochemical oxidation of perfluorooctane sulfonate (PFOS) substitute by modified boron doped diamond (BDD) anodes. Chem Eng J 379:122280. https://doi.org/10.1016/j.cej.2019.122280