

Degradation of Per- and Polyfluoroalkyl Substances

Subjects: Water Resources

Contributor: Xiaoyan Chen, Taoyue Yuan, Xinyu Yang, Shunke Ding, Mengtao Ma

Per- and polyfluoroalkyl substances (PFASs) are an emerging group of persistent organic pollutants in aquatic environments with high levels of toxicity and bioaccumulation. The risks posed by PFASs to the environment and health have attracted increasing attention. To remove them from water, advanced oxidation processes (AOPs), with the merits of high efficiency and low cost, are mainly used. Photo/electrocatalytic heterogeneous AOPs, with the assistance of nanostructured catalysts and external energy in the form of light/electricity, have emerged as one of the most powerful techniques, overcoming the difficulty associated with defluorination and achieving the effective and complete degradation of PFASs in water. The structures of photo/electrocatalysts play a critical role in the production of reactive oxygen species, the electron transfer process, and the degradation pathway and its efficiency.

Keywords: per- and polyfluoroalkyl substances (PFASs) ; heterogeneous advanced oxidation processes (AOPs) ; photo/electrocatalytic degradation ; photocatalysts ; electrocatalysts

1. Introduction

Per- and polyfluoroalkyl substances (PFASs) are an emerging group of persistent organic pollutants in the environment which pose ecological and health risks [1]. PFASs are man-made chemicals that are widely used in various industrial and commercial products; their chemical structure includes a fully fluorinated carbon chain with a terminated functional group attached to it. The most common terminal groups are carboxylic acid ($-\text{COOH}$) and sulfonic acid ($-\text{SO}_3\text{H}$) groups, while the fluorinated carbon chain varies in length and number of branches, containing a number of carbon-fluorine bonds. Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), with structural formulas shown in **Figure 1a**, are the two most commonly detected PFASs. The carbon-fluorine bond in these molecules is one of the strongest single bonds due to its bond energy of 485–582 kJ/mol and its redox potential of F/F^- at 3.6 eV, making it difficult for PFASs to break down naturally [2]. Moreover, the fluorine atoms in PFASs provide a shielding effect that protects the carbon-fluorine bond from chemical and biological attack, further contributing to the persistence of these compounds. On the other hand, toxicological and epidemiological studies have linked PFAS exposure to adverse health effects.

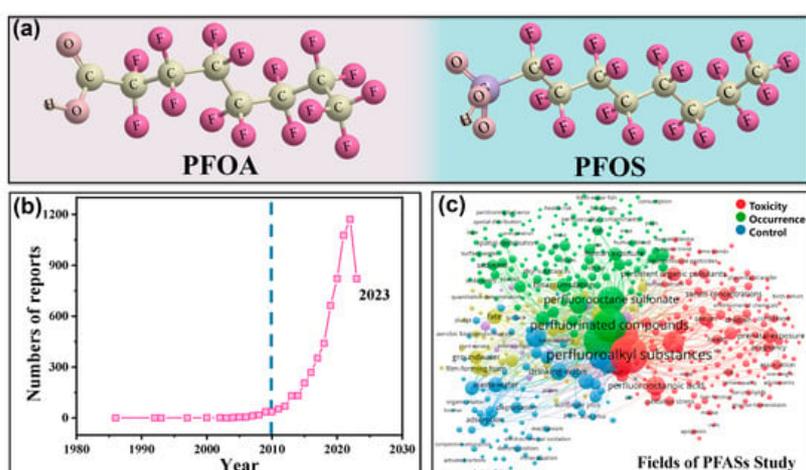


Figure 1. (a) The structures of PFOA and PFOS, and the most commonly occurring PFASs in aquatic environments. (b) Volume of reported research on PFASs. (c) Heat map of works on PFASs, mainly addressing toxicity, occurrence, and control. Data collected from Web of Science (up to 2023).

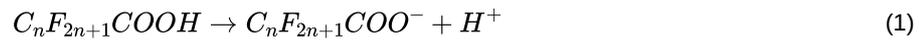
Recent years have witnessed a boom in studies of PFASs, including strategies for their control in water, as displayed in **Figure 1b,c**. These strategies can be categorized into three principal types, i.e., physical separation [3][4], biological treatment [5], and chemical degradation (oxidation and reduction processes) [6][7][8][9]. Physical removal technologies, including adsorption, ion exchange, reverse osmosis, and nanofiltration, either have low PFAS elimination efficiency or

high cost [4]. These non-destructive processes may generate waste such as spent adsorbents that can give rise to re-contamination with their re-entry into the environment. Biological degradation and chemical degradation are destructive technologies that permanently remove PFASs from water, but biodegradations are incomplete, have slow rates, and are highly dependent on environmental conditions [10]. Traditional wet chemical oxidation can barely break the very strong C–F bonds, whereas advanced oxidation processes (AOPs), originally introduced by Glaze in 1987 and distinguished by employing free radicals as highly reactive oxidant species, are considered to be highly efficient and have strong potential for the complete mineralization of PFASs [11][12]. To overcome the high overpotential of defluorination from C–F bonds and accelerate decomposition, more effective AOPs have been developed by introducing catalysts and external energy (light, electricity, heat, ultrasound, etc.) to lower the activation energy and overpotential of PFAS degradation reactions [13][14][15][16]. Energy in the forms of light and electricity is more appropriate for in situ use, as such approaches are relatively low-cost and environmentally friendly. Therefore, photocatalytic and electrocatalytic AOPs in heterogeneous systems are promising for the efficient and complete removal of PFASs in practice.

2. Fundamentals of PFAS Degradation by AOPs

2.1. General Pathways and ROS for PFAS Degradation

The degradation by AOPs of PFASs occurring in water environments starts with their hydrolysis products (Equation (1)). Below, perfluorocarboxylic acid (PFCA, $C_nF_{2n+1}COOH$) represents the PFAS, while the effective ROS is represented by $\bullet OH$. The degradation mechanisms of PFASs by AOPs are closely linked to ROS and their effective sites of action. However, these pathways can be summarized as a general reaction course [17]. Specifically, the oxidation of $C_nF_{2n+1}COO^-$ to $C_nF_{2n+1}COO\bullet$ (Equation (2)) is initiated by radicals (e.g., $\bullet OH$) generated from activated oxidizing agents [18]. Light and electrical energy can also trigger this reaction, utilizing, for example, photogenerated holes (h^+) under ultraviolet radiation or the electron transfer process at the anode [19]. Subsequently, spontaneous decarboxylation of $C_nF_{2n+1}COO\bullet$ occurs due to its instability (Equation (3)), and the resulting perfluoroalkyl radicals $C_nF_{2n+1}\bullet$ transform into $C_nF_{2n+1}OH$ via hydroxylation (Equation (4)) [20]. After the spontaneous elimination of HF from $C_nF_{2n+1}OH$ (Equation (5)), the resulting acyl halide, $C_{n-1}F_{2n-1}COF$, undergoes a hydrolysis process (Equation (6)), generating a short-chain PFCA ($C_{n-1}F_{2n-1}COO^-$). Afterwards, this decarboxylation-hydroxylation-elimination-hydroxylation (DHEH) procedure is performed repeatedly, with the remove of a CF_2 unit and the release of CO_2 and HF in each cycle (Equations (2)–(6)) until complete mineralization is achieved [21][22]. The general degradation pathways of perfluorosulfonic acid (PFSA) are similar, but with the initial oxidation of $C_nF_{2n+1}SO_3^-$ to $C_nF_{2n+1}\bullet$ by ROS attacking the C–S bond [23]. The resulting product then enters the defluorination cycle, similarly to PFCA.



Effective ROS in AOPs of PFASs vary based on the oxidizing agents and their activation methods. Free radicals, such as $\bullet OH$, sulfate radicals ($SO_4^{\bullet-}$), and superoxide radicals ($\bullet O_2^-$), as well as nonradicals like singlet oxygen (1O_2) and holes (h^+), have been identified as dominant ROS that contribute individually or synergistically to the defluorination and destruction of PFASs through advanced oxidation [24]. Fenton and Fenton-like processes, using hydrogen peroxide (H_2O_2) as the oxidant, generate $\bullet OH$ as the effective ROS when activated by Fe^{2+} or other transition metal-based chemicals or materials. Activated persulfate systems, utilizing persulfate (PDS, $S_2O_8^{2-}$) or peroxymonosulfate (PMS, HSO_5^-), primarily

generate $\text{SO}_4^{\bullet-}$ as the dominant ROS and exhibit reactivity due to the high redox potential (+ 2.5 V–3.1 V) and long lifetime (3.4×10^{-5} s) of $\text{SO}_4^{\bullet-}$ [25][26]. Meanwhile, it should be noted that the activation methods of PMS make a big difference to the types of ROS, e.g., $\text{SO}_4^{\bullet-}$ via activation with carbon materials, $\text{SO}_4^{\bullet-}$ and $\bullet\text{OH}$ via thermal and radiation activation, $\text{SO}_4^{\bullet-}$ and peroxymonosulfate anion radicals ($\text{SO}_5^{\bullet-}$) via transition metal activation, and $\bullet\text{O}_2^-$ and $^1\text{O}_2$ via alkali activation [27]. In addition, photogenerated h^+ acts as a powerful ROS that directly oxidizes PFASs or converts $\text{H}_2\text{O}/\text{O}_2$ to $\bullet\text{OH}/\bullet\text{O}_2^-$, thereby generating more ROS [28]. Electrochemical processes induce the rapid generation of different ROS at the anode or facilitate electron transfer to the anode [29].

2.2. Principles of Photocatalytic AOPs for PFAS

Photocatalytic AOPs for PFAS are developed based on direct photo-degradation, achieved by breaking apart the C–F bonds using light of a specific wavelength. The direct photolysis process requires a match between the adsorption spectrum of the chemical bonds and the emission spectrum of the light, with the wavelength of the light playing a crucial role [30]. For example, PFOA has demonstrated strong UV adsorption and fast degradation at 185 nm [31][32], while light with a wavelength above 220 nm is barely absorbed by PFASs [33][34]. In photocatalytic AOPs of PFASs, the indirect photo-oxidation process is characterized by decarboxylation followed by defluorination, believed to be related to the photoinduced holes that exhibit a strong oxidizing capacity for organics. These holes work synergistically with other ROS to enhance PFAS degradation [35][36]. The system of photocatalytic AOPs consists of three components: the light, oxidant, and photocatalyst. There are two principles of PFAS degradation in photocatalytic AOPs: direct oxidation by photogenerated holes and co-oxidation with other ROS that are generated at the surface of catalysts with the assistance of the holes. The general process of PFAS degradation in photocatalytic AOPs can be described as follows: (1) Catalysts absorb light with energy ($h\nu$) equal to or greater than the band gap, which excites electrons from the valence band (VB) to the conduction band (CB), creating holes in the VB. (2) The generated electron–hole (e^- – h^+) pairs migrate to the surface of catalysts and react with the adsorbed PFAS. (3) The e^- – h^+ pairs react with precursors and generate ROS which assist in PFAS decomposition.



The general mechanism of photocatalytic AOPs for PFAS degradation is summarized in **Figure 2**, where the PFAS is represented by PFAC. Photocatalysts play a crucial role in this process, as they are responsible for generating effective ROS and binding PFAS molecules. Both of these factors determine the efficiency of degradation [23]. Therefore, the construction and structure engineering of photocatalysts have garnered significant research interest.

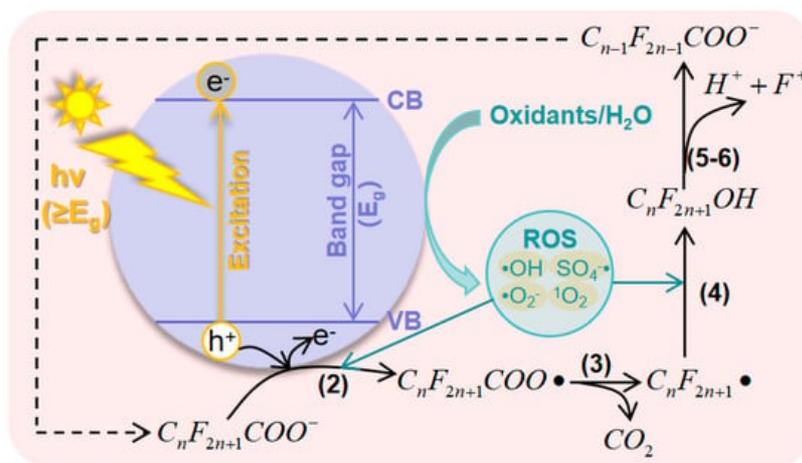


Figure 2. Mechanisms of photocatalytic AOPs for the degradation of PFASs.

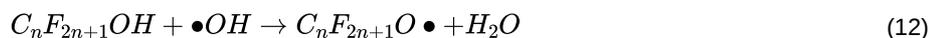
2.3. Principles of Electrocatalytic AOPs for PFASs

There are two types of electrocatalytic AOPs for PFASs: direct electro-oxidation and indirect electrochemical oxidation. Direct electro-oxidation is a simple AOP that occurs on the surface of an electrode (anode) with a direct transfer of electrons. It relies on the in situ generation of ROS (e.g., $\bullet\text{OH}$) or the direct transfer of electrons from the PFAS to the anode [37]. On the other hand, indirect electrochemical oxidation processes are the primary electrocatalytic AOP for

organics treatment. Unlike direct electro-oxidation, electrons in this process act as mediators or assist in the generation of powerful ROS [29]. For example, the degradation of PFASs starts with the release of electrons, forming $C_nF_{2n+1}COO\bullet$ (Equation (2)); this occurs under an anode potential higher than the oxidation potential of the PFAS [38]. Additionally, electrocatalytic AOPs can produce radicals and oxidants during the electrode process. This includes $\bullet OH$, which is strongly adsorbed onto the anode surface (M), as shown in Equation (9), H_2O_2 from the dimerization of $\bullet OH$ (Equation (10)), and ozone (O_3) from the discharge of water molecules (Equation (11)) [39]. These products are highly reactive with certain intermediate products during the decarboxylation and defluorination processes of PFASs, contributing to the efficiency of degradation.



The general mechanism of electrocatalytic AOPs for PFAS degradation is illustrated in **Figure 3**. According to previous studies, after the formation of $C_nF_{2n+1}\bullet$ [40], there several approaches for further mineralization. Process (a) and (b) initially undergo a reaction with $\bullet OH$ to form $C_nF_{2n+1}OH$ (Equation (4)). In process (a), reactions from Equation (12) to Equation (13) occur [41], whereas in process (b), reactions from Equation (14) to Equation (16) take place [42][43]. Aside from $\bullet OH$, other anodic ROS such as O_2 also react with $C_nF_{2n+1}\bullet$ (Equation (17)), and the oxidation product $C_nF_{2n+1}OO\bullet$ can react with other perfluoro-alkoxy radicals ($R_FCOO\bullet$) (Equation (18)). The resulting $C_{n-1}F_{2n-1}\bullet$ then decomposes into $C_{n-1}F_{2n-1}\bullet$ for further degradation in a new cycle (Equation (19)) [40][41][42][44][45]. The third pathway (c) follows the reactions from Equation (17) to Equation (19).



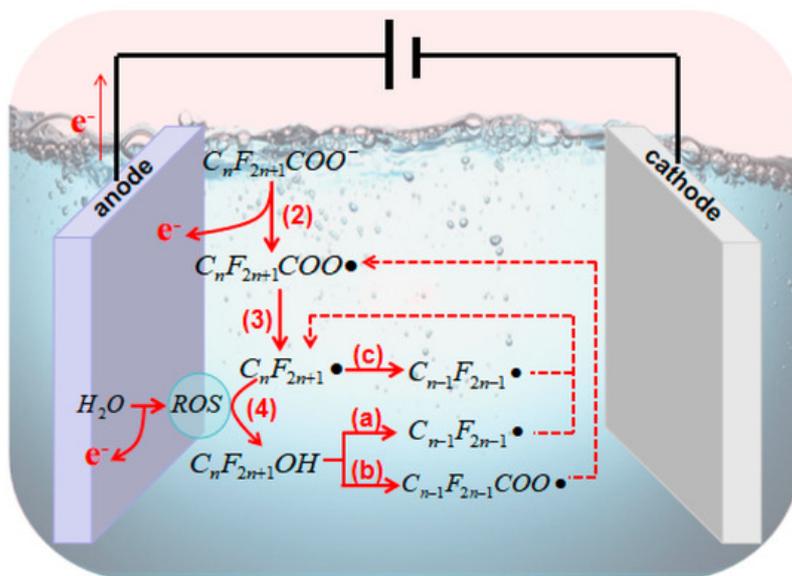


Figure 3. Mechanisms of electrocatalytic AOPs for the degradation of PFASs.

In electrocatalytic processes, oxidation primarily occurs on the anode. Therefore, the choice of anode materials (i.e., electrocatalysts) plays a crucial role in electrocatalytic AOPs for PFAS degradation. The behavior of PFAS degradation can vary depending on the type of anode material used. Anode materials are classified into two types based on the interactions between the adsorbed $\bullet\text{OH}$ on the anode surface and the degradation of organics: active anodes and nonactive anodes. Active anodes, such as $\text{Ti}/\text{SnO}_2\text{-Sb}/\text{MnO}_2$ [40], have a low potential for O_2 evolution and are distinguished from non-active anodes, such as $\text{Ti}/\text{SnO}_2\text{-Sb}$ [46], by their ability to transform $\text{M}(\bullet\text{OH})$ into strong oxidants. Generally, anode materials with higher O_2 -evolution potential exhibit weaker interactions between $\text{M}(\bullet\text{OH})$ and their surface, but they have higher reactivity towards PFASs [29].

3. Photocatalysts in AOPs for PFAS Degradation

3.1. Metal Oxide-Based Materials

Metal oxides, such as TiO_2 , In_2O_3 , and Ga_2O_3 , have long been used as traditional semiconductors in the photocatalytic degradation of organics in water. These metal oxides have been extensively studied for PFAS degradation [23][47][48][49]. TiO_2 -based materials, in particular, have been widely used as photocatalysts since the discovery of water splitting on a TiO_2 anode by Fujishima and Honda in 1972 [50]. Though TiO_2 has shown promise in heterogeneous photocatalysis due to its strong UV absorption, non-toxicity, and long-term photostability, it is not efficient for photocatalytic PFAS degradation. This is due to its narrow spectral range, wide bandgap (3.0 eV for the rutile phase and 3.0 eV for the anatase phase), low electron-hole separation efficiency, and poor adsorption performance. Therefore, modifications of TiO_2 are necessary to enhance its photocatalytic activity. Strategies for modification include metal/nonmetal element doping, carbon material loading, and heterostructure construction. To date, doping with Fe [51], Cu [51], Pb [48][52], Pt [53], Pd [54], Ag [55] in TiO_2 for enhanced PFAS degradation has been studied, as well as the co-doping of metals, such as Fe/Nb [56]. Metal doping involves controlling the doping amount and regulating the pH of the solution to avoid the competitive adsorption of OH^- on the catalyst surface under alkaline conditions.

In_2O_3 is a PFAS affinity material with a narrow bandgap of 2.8 eV, exceptional photocatalytic activity, and sensitivity to visible light. When compared to TiO_2 , In_2O_3 has shown a remarkable 8.4-fold increase in the degradation rate coefficient of a PFAS (PFOA) under UV irradiation. These findings suggest it is a promising photocatalyst for PFAS decomposition [23]. Modifications are necessary for In_2O_3 due to its limitations, i.e., its low specific surface area and the rapid recombination of photogenerated electron-hole pairs. One effective approach is the generation of oxygen vacancies on the In_2O_3 surface, which enhances its photocatalytic performance. Additionally, nanostructures like nanospheres [49], (porous) nanosheets, and nanocubes [57][58] have been developed to provide adsorption sites for PFOA and oxygen atom binding sites in the carboxyl groups. These modifications ultimately contribute to the improved photocatalytic decomposition of PFOA. Several composite materials have been reported, such as $\text{g-C}_3\text{N}_4\text{-In}_2\text{O}_3$ [59], $\text{CeO}_2\text{-In}_2\text{O}_3$ [60], and $\text{MnOx-In}_2\text{O}_3$ [61].

Ga_2O_3 has excellent conductivity and tunable optical properties, despite its wide band-gap (4.9 eV). Studies have demonstrated its remarkable UV photocatalytic activity against PFASs, specifically in the context of PMS-assisted

photocatalytic AOPs. The $\text{Ga}_2\text{O}_3/\text{PMS}/\text{UV}$ system, with $\text{SO}_4^{\bullet-}$ and $\bullet\text{O}_2^-$ as key ROS, achieves 100% degradation within 60 min [62].

3.2. Bi-Based Materials

Bismuth (Bi)-based photocatalysts have emerged as one of the most promising photocatalytic materials for catalysis, primarily due to their non-toxicity, high stability, and low cost. Commonly used Bi-based compounds for PFAS photocatalytic AOPs include bismuth oxyhalides (BiOX , where X is Cl, Br, I), bismuth ferrite (BiFeO_3 , BFO), bismuth phosphate (BiPO_4), and bismuth hydroxyphosphate ($\text{Bi}_3\text{O}(\text{OH})(\text{PO}_4)_2$, BiOHP).

BiOX is a 2D layered compound with alternating double X ion layers and Bi_2O_2 layers along the c-axis. An internal electric field is formed between the halide planes and Bi_2O_2 layers, promoting faster charge transfer, enhanced redox potential, and excellent photocatalytic performance for effective PFAS degradation [63]. BiOI has a narrow bandgap ($E_g = 1.67\text{--}1.92$ eV) and high visible light absorption, showing great potential for applications. However, the narrow bandgap leads to the easy recombination of photoinduced e^-/h^+ pairs, which affects the photocatalytic activity [64]. Researchers have synthesized Br-doped BiOI ($\text{BiOI}_{0.95}\text{Br}_{0.05}$) for the photocatalytic degradation of PFOA [65]. Br doping not only increases PFOA adsorption but also expands the UV absorption range, leading to a significant enhancement in photocatalytic activity. However, the impact of non-metals on the structural properties of the semiconductor, in terms of stability, reproducibility, loading capacity, and practical applications of BiOI , requires further investigation. BiOCl , another noteworthy semiconductor with an indirect bandgap (E_g ranging from 2.62 to 3.46 eV) possesses excellent electronic and optical properties and has become a popular photocatalytic material [66].

3.3. Other Compounds and Composites

In addition to metal-oxides and Bi-based materials, various photocatalysts have been employed in photocatalytic AOPs for PFAS degradation. These include metal/transition metal-based materials, metal-free materials, and modified composite materials. Qian et al. proposed a heterogeneous photocatalytic degradation mechanism for PFOA using Fe-zeolite under UVA irradiation (wavelength range: 320–420 nm) with O_2 as the terminal oxidant [67]. This Fe-zeolite catalyst, compared to homogeneous Fe^{3+} , exhibits a broader light absorption range and can oxidize Fe^{2+} to Fe^{3+} in the presence of O_2 , generating reactive species that contribute to PFAS mineralization. Other photocatalysts, such as samarium doped ferrite [68] and platinum-modified indium oxide nanorods (Pt/IONRs) [69], have also demonstrated significant PFOA degradation (48.6% and 98.0%) within a short period of time (1 h) in photocatalytic AOPs. The high degradation efficiency of Pt/IONRs can be attributed to Pt loading, the rod-like structure of the catalyst, and the presence of surface oxygen vacancies, which promote light harvesting, enhance the separation efficiency of the photogenerated charge carriers, and accelerate PFOA degradation.

4. Electrocatalysts in AOPs for PFAS Degradation

4.1. BDD-Based Materials

Boron-doped diamond (BDD) is one of the most frequently used anode materials in the electrocatalytic degradation of PFASs, owing to its wide operational potential window, excellent chemical stability, and high oxidation potential (2.7 V vs. SHE) [42][70][71]. The BDD electrode plays a crucial role in the direct electrochemical oxidation of PFASs at low current densities, rather than relying on the $\bullet\text{OH}$ oxidation process at high current densities [9][72]. BDD films have been proven to be effective anodic electrocatalysts for PFOS degradation [71], with electron transfer from PFOS to the anode resulting in the formation of final products such as SO_4^{2-} , F^- , CO_2 and a small amount of trifluoroacetic acid. However, the widespread application of BDD as an anode material in electrocatalytic AOPs for PFASs is limited due to its high cost and a lack of suitable electrode substrates for BDD. Metals and nonmetals like Ta, Nb, W, and Si have been investigated as BDD substrates, and Si/BDD has been found to be a cost-effective option for PFOS degradation (>90%) [73][74].

4.2. Metal Oxide-Based Materials

The utilization of metal oxides as electrode materials has revealed the drawbacks associated with metal electrodes, such as lower oxygen evolution overpotential and susceptibility to oxidation. Additionally, it has made it possible to overcome the limitations of BDD electrodes, including low conductivity and low efficiency in terms of utilizing $\bullet\text{OH}$ radicals [75]. Currently, metal oxides commonly used as electrode materials include SnO_2 , PbO_2 , TiO_2 , MnO_2 , and others. Among these, SnO_2 and PbO_2 demonstrate outstanding electrocatalytic oxidation performance, with a higher overpotential of O_2 evolution, making them suitable for the degradation of organics.

SnO₂, a semiconductor with a bandgap of 3.5eV, faces challenges in its direct use as an electrode material due to its high resistance. However, its conductivity can be improved through doping [76][77][78], particularly with antimony (Sb) [40][79]. In addition, SnO₂-Sb electrodes exhibit a high oxygen evolution potential, which contributes to their extensive application in PFAS degradation [40][42][80]. By doping Ti/SnO₂-Sb with multiple metals, a PFOA removal rate of 93.3% can be achieved [40][42]. It is important to note that the presence of SO₄²⁻ in the solution can cover the active sites on the electrode. This reduces the production of •OH radicals, subsequently decreasing the PFOA removal rate [80].

PbO₂ anodes offer several advantages for efficient PFAS degradation, such as low processing costs, simple preparation, high conductivity, and a high oxygen evolution potential [81][82]. However, the issue of PbO₂ detachment in Ti/PbO₂ electrodes hampers their stability. To address this, Ti/SnO₂-Sb/PbO₂, and TiO₂-Nanotubes (NTs)/Ag₂O/PbO₂ electrodes have been developed, effectively enhancing the stability and electrochemical degradation capability with the assistance of an interlayer [83][84][85]. A study was conducted [86], highlighting the contribution of interlayer metal/metal oxide anodes to the efficiency of PFOS degradation. However, PbO₂ electrodes are susceptible to Pb²⁺ leaching [81][82]; this can be mitigated through doping with elements to reduce the grain size, increase the electroactive surface area, improve the oxygen evolution potential, and enhance electron migration ability. Doping with cerium (Ce), ytterbium (Yb), and zirconium (Zr) has resulted in removal rates of over 88% for PFOA [44][45][87]. A Ti/SnO₂-Sb/PbO₂-Ce electrode exhibited removal rates of over 92% for PFDA and PFNA. It is worth noting that the electrochemical degradation rate of PFASs on Ti/SnO₂-based electrodes is influenced by the chain length, emphasizing the need to tailor the catalyst according to the PFAS chain structure [40][44][88]. Carbon-based materials also contribute to electrocatalytic PFAS degradation as substrates for PbO₂. For instance, a 3D graphene (3DG)-PbO₂ anode obtained through electro-deposition exhibited a degradation rate constant for PFOS that was 2.33 times higher than that of PbO₂ anodes [89]. This can be attributed to the porous nanostructures, resulting in a larger specific surface area and multiple electronic transfer channels in the anode.

4.3. Other Compounds and Composites

Composites and hybrids used as anode materials for the electrocatalytic degradation of PFASs can take various forms, employing different mechanisms to improve electrocatalysis performance. However, most of the composites or hybrids used as electrocatalysts are either BDD-based or metal oxide-based materials, as discussed above. Furthermore, there are only a few studies available on this topic, leaving ample room for further research [90][91][92]. In terms of electrode materials, one scarcely investigated type which has demonstrated high reactivity and chemical robustness is the multifunctional single-atom catalyst (SAC). SACs show promise in electrocatalytic PFAS degradation [93].

5. Conclusions

Material modification methods for enhancing PFAS degradation in photocatalytic and electrocatalytic AOPs are summarized as follows:

- (1) For catalysts in the photocatalytic oxidation of PFAS systems, current research primarily focuses on improving catalyst activity by addressing the rapid recombination of photogenerated e⁻-h⁺. Methods include introducing surface defects or oxygen vacancies, metal-doping, heterojunction construction, and crystal facet regulation [28][61][63][64][94][95][96][97]. Furthermore, material composites and morphology regulation have been utilized to enhance reaction probabilities between PFASs and active groups, effectively enhancing the efficiency of PFAS degradation [17][28][98][99].
- (2) For catalysts in the electrocatalytic oxidation of PFAS systems, current research mainly focuses on increasing the yield of active groups through various methods [60][94][100]. Additionally, enhancing the efficiency of electron transfer and mass transfer processes is achieved through metal loading and constructing nano 3D structures [20][83][89][100]. The stability of electrodes is also improved through the construction of intermediate layers [40][101].

References

1. Sadia, M.; Nollen, I.; Helmus, R.; ter Laak, T.L.; Béen, F.; Praetorius, A.; van Wezel, A.P. Occurrence, Fate, and Related Health Risks of PFAS in Raw and Produced Drinking Water. *Environ. Sci. Technol.* 2023, 57, 3062–3074.
2. Dong, C.; Huang, F.; Deng, H.; Schaffrath, C.; Spencer, J.B.; O'Hagan, D.; Naismith, J.H. Crystal structure and mechanism of a bacterial fluorinating enzyme. *Nature* 2004, 427, 561–565.
3. Gagliano, E.; Sgroi, M.; Falciglia, P.P.; Vagliasindi, F.G.A.; Roccaro, P. Removal of poly- and perfluoroalkyl substances (PFAS) from water by adsorption: Role of PFAS chain length, effect of organic matter and challenges in adsorbent regeneration. *Water Res.* 2020, 171, 115381.

4. Chow, S.J.; Croll, H.C.; Ojeda, N.; Klamerus, J.; Capelle, R.; Oppenheimer, J.; Jacangelo, J.G.; Schwab, K.J.; Prasse, C. Comparative investigation of PFAS adsorption onto activated carbon and anion exchange resins during long-term operation of a pilot treatment plant. *Water Res.* 2022, 226, 119198.
5. Bolan, N.; Sarkar, B.; Vithanage, M.; Singh, G.; Tsang, D.C.W.; Mukhopadhyay, R.; Ramadass, K.; Vinu, A.; Sun, Y.; Ramanayaka, S.; et al. Distribution, behaviour, bioavailability and remediation of poly- and per-fluoroalkyl substances (PFAS) in solid biowastes and biowaste-treated soil. *Environ. Int.* 2021, 155, 106600.
6. Bruton, T.K.; Sedlak, D.L. Treatment of Aqueous Film-Forming Foam by Heat-Activated Persulfate Under Conditions Representative of In Situ Chemical Oxidation. *Environ. Sci. Technol.* 2017, 51, 13878–13885.
7. Bao, Y.; Huang, J.; Cagnetta, G.; Yu, G. Removal of F-538 as PFOS alternative in chrome plating wastewater by UV/Sulfite reduction. *Water Res.* 2019, 163, 114907.
8. Cui, J.; Gao, P.; Deng, Y. Destruction of Per- and Polyfluoroalkyl Substances (PFAS) with Advanced Reduction Processes (ARPs): A Critical Review. *Environ. Sci. Technol.* 2020, 54, 3752–3766.
9. Pierpaoli, M.; Szopińska, M.; Wilk, B.K.; Sobaszek, M.; Łuczkiwicz, A.; Bogdanowicz, R.; Fudala-Książek, S. Electrochemical oxidation of PFOA and PFOS in landfill leachates at low and highly boron-doped diamond electrodes. *J. Hazard. Mater.* 2021, 403, 123606.
10. Wackett, L.P. Why Is the Biodegradation of Polyfluorinated Compounds So Rare? *mSphere* 2021, 6, 10–1128.
11. Glaze, W.H.; Kang, J.-W.; Chapin, D.H. The Chemistry of Water Treatment Processes Involving Ozone, Hydrogen Peroxide and Ultraviolet Radiation. *Ozone Sci. Eng.* 1987, 9, 335–352.
12. Yang, L.; Jiao, Y.; Xu, X.; Pan, Y.; Su, C.; Duan, X.; Sun, H.; Liu, S.; Wang, S.; Shao, Z. Superstructures with Atomic-Level Arranged Perovskite and Oxide Layers for Advanced Oxidation with an Enhanced Non-Free Radical Pathway. *ACS Sustain. Chem. Eng.* 2022, 10, 1899–1909.
13. Leonello, D.; Fendrich, M.A.; Parrino, F.; Patel, N.; Orlandi, M.; Miotello, A. Light-Induced Advanced Oxidation Processes as PFAS Remediation Methods: A Review. *Appl. Sci.* 2021, 11, 8468.
14. Broman, J.; Ceja, A.; Godoy, T.; Rivera, D.R.; Dionne, P.; Schipper, J.; Henkemeyer, S.; Cegielski, S.; Wong, G.; Kaur, A.; et al. Destruction of Per- and Polyfluoroalkyl Substances (PFAS) via Lacasse Enzymatic Degradation and Electrochemical Advanced Oxidation. In Proceedings of the 31st Waste-Management Education Research Conference (WERC), Las Cruces, NM, USA, 11–14 April 2021.
15. Xiao, F.; Sasi, P.C.; Alinezhad, A.; Sun, R.; Ali, M.A. Thermal Phase Transition and Rapid Degradation of Forever Chemicals (PFAS) in Spent Media Using Induction Heating. *ACS ES&T Eng.* 2023, 3, 1370–1380.
16. Horikoshi, S.; Sato, S.; Abe, M.; Serpone, N. A novel liquid plasma AOP device integrating microwaves and ultrasounds and its evaluation in defluorinating perfluorooctanoic acid in aqueous media. *Ultrason. Sonochem.* 2011, 18, 938–942.
17. Samy, M.; Ibrahim, M.G.; Fujii, M.; Diab, K.E.; Elkady, M.; Gar Alalm, M. CNTs/MOF-808 painted plates for extended treatment of pharmaceutical and agrochemical wastewaters in a novel photocatalytic reactor. *Chem. Eng. J.* 2021, 406, 127152.
18. Cao, M.H.; Wang, B.B.; Yu, H.S.; Wang, L.L.; Yuan, S.H.; Chen, J. Photochemical decomposition of perfluorooctanoic acid in aqueous periodate with VUV and UV light irradiation. *J. Hazard. Mater.* 2010, 179, 1143–1146.
19. Li, Z.; Zhang, P.; Shao, T.; Li, X. In₂O₃ nanoporous nanosphere: A highly efficient photocatalyst for decomposition of perfluorooctanoic acid. *Appl. Catal. B* 2012, 125, 350–357.
20. Liu, X.; Wei, W.; Xu, J.; Wang, D.; Song, L.; Ni, B.-J. Photochemical decomposition of perfluorochemicals in contaminated water. *Water Res.* 2020, 186, 116311.
21. Song, Z.; Tang, H.; Wang, N.; Zhu, L. Reductive defluorination of perfluorooctanoic acid by hydrated electrons in a sulfite-mediated UV photochemical system. *J. Hazard. Mater.* 2013, 262, 332–338.
22. Bentel, M.J.; Yu, Y.; Xu, L.; Li, Z.; Wong, B.M.; Men, Y.; Liu, J. Defluorination of Per- and Polyfluoroalkyl Substances (PFASs) with Hydrated Electrons: Structural Dependence and Implications to PFAS Remediation and Management. *Environ. Sci. Technol.* 2019, 53, 3718–3728.
23. Li, X.; Zhang, P.; Jin, L.; Shao, T.; Li, Z.; Cao, J. Efficient Photocatalytic Decomposition of Perfluorooctanoic Acid by Indium Oxide and Its Mechanism. *Environ. Sci. Technol.* 2012, 46, 5528–5534.
24. Banayan Esfahani, E.; Asadi Zeidabadi, F.; Zhang, S.; Mohseni, M. Photo-chemical/catalytic oxidative/reductive decomposition of per- and poly-fluoroalkyl substances (PFAS), decomposition mechanisms and effects of key factors: A review. *Environ. Sci. Water Res. Technol.* 2022, 8, 698–728.
25. Ebersson, L. Electron-Transfer Reactions in Organic Chemistry. *Adv. Phys. Org. Chem.* 1982, 18, 79–185.

26. Zhang, H.; Xie, C.; Chen, L.; Duan, J.; Li, F.; Liu, W. Different reaction mechanisms of $\text{SO}_4^{\bullet-}$ and $\bullet\text{OH}$ with organic compound interpreted at molecular orbital level in Co(II)/peroxymonosulfate catalytic activation system. *Water Res.* 2023, 229, 119392.
27. Wang, J.; Wang, S. Activation of persulfate (PS) and peroxymonosulfate (PMS) and application for the degradation of emerging contaminants. *Chem. Eng. J.* 2018, 334, 1502–1517.
28. Duan, L.; Wang, B.; Heck, K.N.; Clark, C.A.; Wei, J.; Wang, M.; Metz, J.; Wu, G.; Tsai, A.-L.; Guo, S.; et al. Titanium oxide improves boron nitride photocatalytic degradation of perfluorooctanoic acid. *Chem. Eng. J.* 2022, 448, 137735.
29. Moreira, F.C.; Boaventura, R.A.R.; Brillas, E.; Vilar, V.J.P. Electrochemical advanced oxidation processes: A review on their application to synthetic and real wastewaters. *Appl. Catal. B* 2017, 202, 217–261.
30. Yadav, S.; Ibrar, I.; Al-Juboori, R.A.; Singh, L.; Ganbat, N.; Kazwini, T.; Karbassiyazdi, E.; Samal, A.K.; Subbiah, S.; Altaee, A. Updated review on emerging technologies for PFAS contaminated water treatment. *Chem. Eng. Res. Des.* 2022, 182, 667–700.
31. Wang, Y.; Zhang, P. Effects of pH on photochemical decomposition of perfluorooctanoic acid in different atmospheres by 185nm vacuum ultraviolet. *J. Environ. Sci.* 2014, 26, 2207–2214.
32. Giri, R.R.; Ozaki, H.; Okada, T.; Taniguchi, S.; Takanami, R. Factors influencing UV photodecomposition of perfluorooctanoic acid in water. *Chem. Eng. J.* 2012, 180, 197–203.
33. Li, F.; Duan, J.; Tian, S.; Ji, H.; Zhu, Y.; Wei, Z.; Zhao, D. Short-chain per- and polyfluoroalkyl substances in aquatic systems: Occurrence, impacts and treatment. *Chem. Eng. J.* 2020, 380, 122506.
34. Wang, S.; Yang, Q.; Chen, F.; Sun, J.; Luo, K.; Yao, F.; Wang, X.; Wang, D.; Li, X.; Zeng, G. Photocatalytic degradation of perfluorooctanoic acid and perfluorooctane sulfonate in water: A critical review. *Chem. Eng. J.* 2017, 328, 927–942.
35. Phan Thi, L.-A.; Do, H.-T.; Lee, Y.-C.; Lo, S.-L. Photochemical decomposition of perfluorooctanoic acids in aqueous carbonate solution with UV irradiation. *Chem. Eng. J.* 2013, 221, 258–263.
36. Qanbarzadeh, M.; Wang, D.; Ateia, M.; Sahu, S.P.; Cates, E.L. Impacts of Reactor Configuration, Degradation Mechanisms, and Water Matrices on Perfluorocarboxylic Acid Treatment Efficiency by the UV/Bi₃O(OH)(PO₄)₂ Photocatalytic Process. *ACS ES&T Eng.* 2021, 1, 239–248.
37. Hossain, M.S.; Mollah, M.Y.A.; Susan, M.A.B.H.; Islam, M.M. Role of in situ electrogenerated reactive oxygen species towards degradation of organic dye in aqueous solution. *Electrochim. Acta* 2020, 344, 136146.
38. Liu, X.Y.; Zhang, Y.Q.; Xia, X.H.; Shi, S.J.; Lu, Y.; Wang, X.L.; Gu, C.D.; Tu, J.P. Self-assembled porous NiCo₂O₄ hetero-structure array for electrochemical capacitor. *J. Power Sour.* 2013, 239, 157–163.
39. Panizza, M.; Cerisola, G. Direct and Mediated Anodic Oxidation of Organic Pollutants. *Chem. Rev.* 2009, 109, 6541–6569.
40. Lin, H.; Niu, J.; Ding, S.; Zhang, L. Electrochemical degradation of perfluorooctanoic acid (PFOA) by Ti/SnO₂–Sb, Ti/SnO₂–Sb/PbO₂ and Ti/SnO₂–Sb/MnO₂ anodes. *Water Res.* 2012, 46, 2281–2289.
41. Niu, J.; Lin, H.; Gong, C.; Sun, X. Theoretical and Experimental Insights into the Electrochemical Mineralization Mechanism of Perfluorooctanoic Acid. *Environ. Sci. Technol.* 2013, 47, 14341–14349.
42. Zhuo, Q.; Deng, S.; Yang, B.; Huang, J.; Yu, G. Efficient Electrochemical Oxidation of Perfluorooctanoate Using a Ti/SnO₂-Sb-Bi Anode. *Environ. Sci. Technol.* 2011, 45, 2973–2979.
43. Lin, H.; Niu, J.; Xu, J.; Huang, H.; Li, D.; Yue, Z.; Feng, C. Highly Efficient and Mild Electrochemical Mineralization of Long-Chain Perfluorocarboxylic Acids (C₉–C₁₀) by Ti/SnO₂–Sb–Ce, Ti/SnO₂–Sb/Ce–PbO₂, and Ti/BDD Electrodes. *Environ. Sci. Technol.* 2013, 47, 13039–13046.
44. Niu, J.; Lin, H.; Xu, J.; Wu, H.; Li, Y. Electrochemical Mineralization of Perfluorocarboxylic Acids (PFCAs) by Ce-Doped Modified Porous Nanocrystalline PbO₂ Film Electrode. *Environ. Sci. Technol.* 2012, 46, 10191–10198.
45. Ma, Q.; Liu, L.; Cui, W.; Li, R.; Song, T.; Cui, Z. Electrochemical degradation of perfluorooctanoic acid (PFOA) by Yb-doped Ti/SnO₂–Sb/PbO₂ anodes and determination of the optimal conditions. *RSC Adv.* 2015, 5, 84856–84864.
46. Wang, K.; Huang, D.; Wang, W.; Ji, Y.; Niu, J. Enhanced perfluorooctanoic acid degradation by electrochemical activation of peroxymonosulfate in aqueous solution. *Environ. Int.* 2020, 137, 105562.
47. Fu, C.; Xu, X.; Zheng, C.; Liu, X.; Zhao, D.; Qiu, W. Photocatalysis of aqueous PFOA by common catalysts of In₂O₃, Ga₂O₃, TiO₂, CeO₂ and CdS: Influence factors and mechanistic insights. *Environ. Geochem. Health* 2022, 44, 2943–2953.
48. Chen, M.-J.; Lo, S.-L.; Lee, Y.-C.; Kuo, J.; Wu, C.-H. Decomposition of perfluorooctanoic acid by ultraviolet light irradiation with Pb-modified titanium dioxide. *J. Hazard. Mater.* 2016, 303, 111–118.

49. Zhao, B.; Li, X.; Yang, L.; Wang, F.; Li, J.; Xia, W.; Li, W.; Zhou, L.; Zhao, C. β -Ga₂O₃ Nanorod Synthesis with a One-step Microwave Irradiation Hydrothermal Method and its Efficient Photocatalytic Degradation for Perfluorooctanoic Acid. *Photochem. Photobiol.* 2015, 91, 42–47.
50. Fujishima, A.; Honda, K. Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature* 1972, 238, 37–38.
51. Chen, M.-J.; Lo, S.-L.; Lee, Y.-C.; Huang, C.-C. Photocatalytic decomposition of perfluorooctanoic acid by transition-metal modified titanium dioxide. *J. Hazard. Mater.* 2015, 288, 168–175.
52. Chowdhury, N.; Choi, H. Photocatalytic degradation of perfluorooctanoic acid on Pb-doped TiO₂ coated with reduced graphene oxide. *Water Environ. Res.* 2023, 95, e10871.
53. Li, M.; Yu, Z.; Liu, Q.; Sun, L.; Huang, W. Photocatalytic decomposition of perfluorooctanoic acid by noble metallic nanoparticles modified TiO₂. *Chem. Eng. J.* 2016, 286, 232–238.
54. Liu, Q.; Yu, Z.-b.; Zhang, R.-h.; Li, M.-j.; Chen, Y.; Wang, L.; Kuang, Y.; Zhang, B.; Zhu, Y.-h. Photocatalytic Degradation of Perfluorooctanoic Acid by Pd-TiO₂ Photocatalyst. *Huanjing Kexue* 2015, 36, 2138–2146.
55. Tian, A.; Wu, Y.; Mao, K. Enhanced Performance of Surface Modified TiO₂ Nanotubes for the Decomposition of Perfluorooctanoic Acid. In *Proceedings of the International Conference on Materials Science, Resource and Environmental Engineering (MSREE)*, Xian, China, 10–11 December 2016.
56. Estrellan, C.R.; Salim, C.; Hinode, H. Photocatalytic decomposition of perfluorooctanoic acid by iron and niobium co-doped titanium dioxide. *J. Hazard. Mater.* 2010, 179, 79–83.
57. Li, Z.; Zhang, P.; Shao, T.; Wang, J.; Jin, L.; Li, X. Different nanostructured In₂O₃ for photocatalytic decomposition of perfluorooctanoic acid (PFOA). *J. Hazard. Mater.* 2013, 260, 40–46.
58. Li, Z.; Zhang, P.; Li, J.; Shao, T.; Wang, J.; Jin, L. Synthesis of In₂O₃ porous nanoplates for photocatalytic decomposition of perfluorooctanoic acid (PFOA). *Catal. Commun.* 2014, 43, 42–46.
59. Xu, C.; Qiu, P.; Chen, H.; Jiang, F.; Wang, X. Fabrication of two-dimensional indium oxide nanosheets with graphitic carbon nitride nanosheets as sacrificial templates. *Mater. Lett.* 2019, 242, 24–27.
60. Jiang, F.; Zhao, H.; Chen, H.; Xu, C.; Chen, J. Enhancement of photocatalytic decomposition of perfluorooctanoic acid on CeO₂/In₂O₃. *RSC Adv.* 2016, 6, 72015–72021.
61. Wu, Y.; Li, Y.; Fang, C.; Li, C. Highly Efficient Degradation of Perfluorooctanoic Acid over a MnO_x-Modified Oxygen-Vacancy-Rich In₂O₃ Photocatalyst. *ChemCatChem* 2019, 11, 2297–2303.
62. Xu, B.; Zhou, J.L.; Altaee, A.; Ahmed, M.B.; Jahir, M.A.H.; Ren, J.; Li, X. Improved photocatalysis of perfluorooctanoic acid in water and wastewater by Ga₂O₃/UV system assisted by peroxymonosulfate. *Chemosphere* 2020, 239, 124722.
63. Wang, J.; Cao, C.; Zhang, Y.; Zhang, Y.; Zhu, L. Underneath mechanisms into the super effective degradation of PFOA by BiOF nanosheets with tunable oxygen vacancies on exposed (101) facets. *Appl. Catal. B* 2021, 286, 119911.
64. Li, Y.; Wang, J.; Yao, H.; Dang, L.; Li, Z. Efficient decomposition of organic compounds and reaction mechanism with BiOI photocatalyst under visible light irradiation. *J. Mol. Catal. A Chem.* 2011, 334, 116–122.
65. Li, T.; Wang, C.; Wang, T.; Zhu, L. Highly efficient photocatalytic degradation toward perfluorooctanoic acid by bromine doped BiOI with high exposure of (001) facet. *Appl. Catal. B* 2020, 268, 118442.
66. Zhang, K.-L.; Liu, C.-M.; Huang, F.-Q.; Zheng, C.; Wang, W.-D. Study of the electronic structure and photocatalytic activity of the BiOCl photocatalyst. *Appl. Catal. B* 2006, 68, 125–129.
67. Qian, L.; Georgi, A.; Gonzalez-Olmos, R.; Kopinke, F.-D. Degradation of perfluorooctanoic acid adsorbed on Fe-zeolites with molecular oxygen as oxidant under UV-A irradiation. *Appl. Catal. B Environ.* 2020, 278, 119283.
68. Luo, D.; Yuan, J.; Zhou, J.; Zou, M.; Xi, R.; Qin, Y.; Shen, Q.; Hu, S.; Xu, J.; Nie, M.; et al. Synthesis of samarium doped ferrite and its enhanced photocatalytic degradation of perfluorooctanoic acid (PFOA). *Opt. Mater.* 2021, 122, 111636.
69. Xu, J.; Wu, M.; Yang, J.; Wang, Z.; Chen, M.; Teng, F. Efficient photocatalytic degradation of perfluorooctanoic acid by a wide band gap p-block metal oxyhydroxide InOOH. *Appl. Surf. Sci.* 2017, 416, 587–592.
70. Ochiai, T.; Iizuka, Y.; Nakata, K.; Murakami, T.; Tryk, D.A.; Fujishima, A.; Koide, Y.; Morito, Y. Efficient electrochemical decomposition of perfluorocarboxylic acids by the use of a boron-doped diamond electrode. *Diamond Relat. Mater.* 2011, 20, 64–67.
71. Carter, K.E.; Farrell, J. Oxidative Destruction of Perfluorooctane Sulfonate Using Boron-Doped Diamond Film Electrodes. *Environ. Sci. Technol.* 2008, 42, 6111–6115.
72. Zhi, J.-F.; Wang, H.-B.; Nakashima, T.; Rao, T.N.; Fujishima, A. Electrochemical Incineration of Organic Pollutants on Boron-Doped Diamond Electrode. Evidence for Direct Electrochemical Oxidation Pathway. *J. Phys. Chem. B* 2003,

73. Sukeesan, S.; Boontanon, N.; Boontanon, S.K. Improved electrical driving current of electrochemical treatment of Per- and Polyfluoroalkyl Substances (PFAS) in water using Boron-Doped Diamond anode. *Environ. Technol. Innov.* 2021, 23, 101655.
74. Barisci, S.; Suri, R. Electrooxidation of short and long chain perfluorocarboxylic acids using boron doped diamond electrodes. *Chemosphere* 2020, 243, 125349.
75. Zhao, G.; Zhang, Y.; Lei, Y.; Lv, B.; Gao, J.; Zhang, Y.; Li, D. Fabrication and Electrochemical Treatment Application of a Novel Lead Dioxide Anode with Superhydrophobic Surfaces, High Oxygen Evolution Potential, and Oxidation Capability. *Environ. Sci. Technol.* 2010, 44, 1754–1759.
76. Lou, Z.; Wang, J.; Wang, S.; Xu, Y.; Wang, J.; Liu, B.; Yu, C.; Yu, J. Strong hydrophobic affinity and enhanced •OH generation boost energy-efficient electrochemical destruction of perfluorooctanoic acid on robust ceramic/PbO₂-PTFE anode. *Sep. Purif. Technol.* 2022, 280, 119919.
77. Yang, B.; Jiang, C.; Yu, G.; Zhuo, Q.; Deng, S.; Wu, J.; Zhang, H. Highly efficient electrochemical degradation of perfluorooctanoic acid (PFOA) by F-doped Ti/SnO₂ electrode. *J. Hazard. Mater.* 2015, 299, 417–424.
78. Zhuo, Q.; Xiang, Q.; Yi, H.; Zhang, Z.; Yang, B.; Cui, K.; Bing, X.; Xu, Z.; Liang, X.; Guo, Q.; et al. Electrochemical oxidation of PFOA in aqueous solution using highly hydrophobic modified PbO₂ electrodes. *J. Electroanal. Chem.* 2017, 801, 235–243.
79. Duan, T.; Wen, Q.; Chen, Y.; Zhou, Y.; Duan, Y. Enhancing electrocatalytic performance of Sb-doped SnO₂ electrode by compositing nitrogen-doped graphene nanosheets. *J. Hazard. Mater.* 2014, 280, 304–314.
80. Zhao, H.; Gao, J.; Zhao, G.; Fan, J.; Wang, Y.; Wang, Y. Fabrication of novel SnO₂-Sb/carbon aerogel electrode for ultrasonic electrochemical oxidation of perfluorooctanoate with high catalytic efficiency. *Appl. Catal. B* 2013, 136–137, 278–286.
81. Aquino, J.M.; Rocha-Filho, R.C.; Ruotolo, L.A.M.; Bocchi, N.; Biaggio, S.R. Electrochemical degradation of a real textile wastewater using β-PbO₂ and DSA® anodes. *Chem. Eng. J.* 2014, 251, 138–145.
82. Mukimin, A.; Vistanty, H.; Zen, N. Oxidation of textile wastewater using cylinder Ti/β-PbO₂ electrode in electrocatalytic tube reactor. *Chem. Eng. J.* 2015, 259, 430–437.
83. Song, S.; Zhan, L.; He, Z.; Lin, L.; Tu, J.; Zhang, Z.; Chen, J.; Xu, L. Mechanism of the anodic oxidation of 4-chloro-3-methyl phenol in aqueous solution using Ti/SnO₂-Sb/PbO₂ electrodes. *J. Hazard. Mater.* 2010, 175, 614–621.
84. Zhong, C.; Wei, K.; Han, W.; Wang, L.; Sun, X.; Li, J. Electrochemical degradation of tricyclazole in aqueous solution using Ti/SnO₂-Sb/PbO₂ anode. *J. Electroanal. Chem.* 2013, 705, 68–74.
85. Song, S.; Fan, J.; He, Z.; Zhan, L.; Liu, Z.; Chen, J.; Xu, X. Electrochemical degradation of azo dye C.I. Reactive Red 195 by anodic oxidation on Ti/SnO₂-Sb/PbO₂ electrodes. *Electrochim. Acta* 2010, 55, 3606–3613.
86. Yang, B.; Wang, J.; Jiang, C.; Li, J.; Yu, G.; Deng, S.; Lu, S.; Zhang, P.; Zhu, C.; Zhuo, Q. Electrochemical mineralization of perfluorooctane sulfonate by novel F and Sb co-doped Ti/SnO₂ electrode containing Sn-Sb interlayer. *Chem. Eng. J.* 2017, 316, 296–304.
87. Xu, Z.; Yu, Y.; Liu, H.; Niu, J. Highly efficient and stable Zr-doped nanocrystalline PbO₂ electrode for mineralization of perfluorooctanoic acid in a sequential treatment system. *Sci. Total Environ.* 2017, 579, 1600–1607.
88. Ellis, D.A.; Denkenberger, K.A.; Burrow, T.E.; Mabury, S.A. The Use of ¹⁹F NMR to Interpret the Structural Properties of Perfluorocarboxylate Acids: A Possible Correlation with Their Environmental Disposition. *J. Phys. Chem. A* 2004, 108, 10099–10106.
89. Duan, X.; Wang, W.; Wang, Q.; Sui, X.; Li, N.; Chang, L. Electrocatalytic degradation of perfluorooctane sulfonate (PFOS) on a 3D graphene-lead dioxide (3DG-PbO₂) composite anode: Electrode characterization, degradation mechanism and toxicity. *Chemosphere* 2020, 260, 127587.
90. Ma, Q.; Gao, J.; Moussa, B.; Young, J.; Zhao, M.; Zhang, W. Electrosorption, Desorption, and Oxidation of Perfluoroalkyl Carboxylic Acids (PFCAs) via MXene-Based Electrocatalytic Membranes. *ACS Appl. Mater. Interfaces* 2023, 15, 29149–29159.
91. Han, J.; Zhao, M.; Wu, K.; Hong, Y.; Huang, T.; Gu, X.; Wang, Z.; Liu, S.; Zhu, G. A bifunctional single-atom catalyst assisted by Fe₂O₃ for efficiently electrocatalytic perfluorooctanoic acid degradation by integrating reductive and oxidative processes. *Chem. Eng. J.* 2023, 470, 144270.
92. Wang, Q.; Liu, M.; Zhao, H.; Chen, Y.; Xiao, F.; Chu, W.; Zhao, G. Efficiently degradation of perfluorooctanoic acid in synergic electrochemical process combining cathodic electro-Fenton and anodic oxidation. *Chem. Eng. J.* 2019, 378, 122071.

93. Abdelghafar, F.; Xu, X.; Jiang, S.P.; Shao, Z. Designing single-atom catalysts toward improved alkaline hydrogen evolution reaction. *Mater. Rep. Energy* 2022, 2, 100144.
94. Wang, C.; Zhang, T.; Yin, L.; Ni, C.; Ni, J.; Hou, L.-A. Enhanced perfluorooctane acid mineralization by electrochemical oxidation using Ti³⁺ self-doping TiO₂ nanotube arrays anode. *Chemosphere* 2022, 286, 131804.
95. Liu, X.; Duan, X.; Bao, T.; Hao, D.; Chen, Z.; Wei, W.; Wang, D.; Wang, S.; Ni, B.-J. High-performance photocatalytic decomposition of PFOA by BiOX/TiO₂ heterojunctions: Self-induced inner electric fields and band alignment. *J. Hazard. Mater.* 2022, 430, 128195.
96. Yao, X.; Zuo, J.; Wang, Y.-J.; Song, N.-N.; Li, H.-H.; Qiu, K. Enhanced Photocatalytic Degradation of Perfluorooctanoic Acid by Mesoporous Sb₂O₃/TiO₂ Heterojunctions. *Front. Chem.* 2021, 9, 690520.
97. Yang, Y.; Zheng, Z.; Yang, M.; Chen, J.; Li, C.; Zhang, C.; Zhang, X. In-situ fabrication of a spherical-shaped Zn-Al hydroxalcalite with BiOCl and study on its enhanced photocatalytic mechanism for perfluorooctanoic acid removal performed with a response surface methodology. *J. Hazard. Mater.* 2020, 399, 123070.
98. McQueen, A.D.; Tedrow, O.N.; Ballentine, M.L.; Kennedy, A.J. Demonstration of Photocatalytic Degradation of Per- and Polyfluoroalkyl Substances (PFAS) in Landfill Leachate Using 3D Printed TiO₂ Composite Tiles. *Water Air Soil Pollut.* 2022, 233, 444.
99. Huang, G.; Zhang, G.; Gao, Z.; Cao, J.; Li, D.; Yun, H.; Zeng, T. Enhanced visible-light-driven photocatalytic activity of BiFeO₃ via electric-field control of spontaneous polarization. *J. Alloys Compd.* 2019, 783, 943–951.
100. Wang, Y.; Wang, C.; Luo, P.; Hu, Q. Removal of perfluorooctanoic acid by MWCNT-modified carbon-doped titanium dioxide in a peroxymonosulfate/simulated sunlight system. *Appl. Surf. Sci.* 2023, 614, 156251.
101. Zhuo, Q.; Li, X.; Yan, F.; Yang, B.; Deng, S.; Huang, J.; Yu, G. Electrochemical oxidation of 1H,1H,2H,2H-perfluorooctane sulfonic acid (6:2 FTS) on DSA electrode: Operating parameters and mechanism. *J. Environ. Sci.* 2014, 26, 1733–1739.

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