Supplementary Materials

Carbon–Fluorine Bond Cleavage in PFAS Remediation: Integrating Biological and Emerging Advanced Treatment Technologies

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Table S1. Detailed Comparison of PFAS Defluorination Technologies

Compound	Defluorination Efficiency	Operating conditions/Technology	Advantages	limitations	Technology readiness	Energy consumption	Matrix	References
PFOA	85.32% degradation and 76.96% defluorination	46.18% TOC reduction (Gradient S-doped Cu catalyst)	High degradation and defluorination; low-cost Cu catalyst; effective C-F bond cleavage	Laboratory-scale only; incomplete mineralization; untested for mixed PFAS and real waters; catalyst stability unknown	TRL 3-4	Moderate–high energy demand (−1.8 V, 12 h); low-cost Cu catalyst	aquatic environment	[294]
PFOA	>88.4% was removed within 1 h, > 90% was converted to F^- within 6 h.	Piezoelectric ball milling ($SrTiO_3$@NiO catalyst)	High degradation/defluorination; enhanced piezocatalysis; low-temperature soil remediation	Laboratory-scale; PFOA only; limited reusability; scale-up required	TRL 3-4	Not reported; moderate energy (ball milling)	Soil	[295]
PFOA	96% degradation within 80 min, 85.1% of its activity after five	Visible-light photocatalysis ($Bi_4O_5I_2$–$CaIn_2S_4$/biochar Z-scheme)	High degradation; visible-light active; enhanced charge separation; reusable catalyst; PFAS degradation/CO_2 reduction	Bench-scale; PFOA only; no real-water validation; scale-up and stability unassessed	TRL 2–3	Not reported (visible light driven suggests potentially low operational energy demand)	aquatic environment	[290]
PFOA, PFOS, GenX, OBS, 6:2 FTS	97.04 −99.99% degradation and 96.90 −99.98% within 120 min at 200 mM Cl−	CEC with synergistic hydroxyl and chlorine radicals	Rapid degradation; synergistic oxidation; reusable catalyst	Laboratory-scale; model PFAS only; limited real-water validation; by-product assessment; scale-up required	TRL 2–3	Not reported (electrical driven)	saline and industrial waters	[297]

PFOS, PFOA	37.3 ± 3.6% fluoride release	Electro-oxidation and Electro-Fenton using Ti_4O_7 Magnéli-phase anode	High removal; enhanced degradation/defluorination; low energy; sustainable Ti_4O_7 anode	Laboratory-scale; partial defluorination; limited durability; scale-up required	TRL 3-4	Not reported; low (0.018–0.038 kWh m^{-3})	aquatic environments	[283]
PFCAs, GenX	49.1% degradation and 21.2% defluorination within 5 h, 86.0% PFOA destruction and 25.5% defluorination after 12 h under additive-free conditions	Intensified simulated solar-light photolysis	Catalyst-free; solar-driven; H•-mediated defluorination; mild conditions; sustainable	Moderate degradation/defluorination; UV <300 nm required; laboratory-scale; scale-up require	TRL 2–3	Not reported. Suggests potential for low energy demand if implemented with natural sunlight	under simulated solar light in a catalyst-free environment	[282]
PFAO	75.68% and a degradation rate exceeding 95% within 2 h	VUV/sulfite advanced reduction process (hydrated electron-based)	Efficient degradation/defluorination; enhanced hydrated electrons; low energy; effective in complex waters	Laboratory-scale; VUV/sulfite required; by-product assessment; scale-up required	TRL 3-4	Not reported- low-energy process with optimized VUV irradiation	Aquatic environment	[284]
PFAS	75.8% within 8 h	Sunlight-driven photocatalysis ($CuInS_2$/BiOCl heterojunction)	Sunlight-driven degradation; enhanced C-F cleavage; hydrated electrons; reusable catalyst; low energy	Laboratory-scale; selected PFAS; limited durability; limited real-water validation; scale-up required	TRL 3-4	Not reported; very low (solar-driven)	aqueous environments	[285]
PFOA	100% degradation and up to 69% defluorination	Integrated ARDP system	Integrated adsorption–plasma; adsorbent regeneration; solvent recovery; energy-efficient; minimal secondary waste PFAS streams	Model-based; limited validation; uncertain real-water performance; pilot-scale verification required	TRL 2-3	Not reported; low (waste heat/solvent recovery)	aqueous environments	[278]

GenX	90% degradation in 1 h and 99% defluorination in 6 h	Fe^{3+}/Fe^{2+} redox cycling with singlet oxygen and nitrogen oxide radical	Efficient GenX defluorination; synergistic $^1O_2$/NOx• oxidation; enhanced C-F cleavage; mild conditions	Laboratory-scale; GenX only; $Fe^{3+}/Fe^{2+}/O_2$ dependent; limited real-water validation; scale-up required	TRL 2–3	Not reported- suggests Low. The process relies on chemical redox cycling	aqueous environments a	298]
PFOA	~92% removal	Adsorption-enhanced photocatalysis (PVDF-pyrolyzed F-doped TiO_2)	Adsorption-photocatalysis; enhanced charge transfer; improved efficiency; reusable catalyst; sustainable	Laboratory-scale; PFOA only; light-dependent; limited real-water validation; scale-up required	TRL 2-	Not reported	-	[288]
PFOA	-	Zero-valent metal-enhanced BN/TiO_2 photocatalysis (Mott–Schottky junction)	Enhanced charge separation; improved degradation/defluorination; reusable catalyst; sustainable	Laboratory-scale; PFOA only; light-dependent; limited real-water validation; scale-up required	TRL 2-3	Not reported	aquatic environments	[264]
PFBS	13.46% removal with DOM; UVC/UVA enhanced degradation and defluorination rates	High-temperature pyrolyzed biochar–microbe synergy (HPB900–*Pseudomonas aeruginosa*)	High adsorption; enhanced PFBS degradation/defluorination; DOM-tolerant; low-cost biochar; sustainable	PFBS only; slow biodegradation; laboratory-scale; limited field validation; scale-up required	TRL 3-4	Not reported; suggests low (adsorption/biodegradation)	aquatic environments	[280]
PFOA	>99% removal in synthetic matrices and >91% in real secondary effluent, ~87% defluorination	Polyaniline-based reversible electrosorption integrated with BDD electro-oxidation	Reversible electrosorption; high removal; reusable adsorbent; enhanced defluorination; low energy; scalable flow-cell	Laboratory-scale; PFOA only; BDD oxidation required; mixed PFAS unverified; pilot-scale required	TRL 3-4	Not reported; very low (>20-fold reduction)	aquatic environments	[286]
PFNA, PFOA, PFHpA,	95 %, 100 %, and 97 %, 87.6 %, 84 % removal, 19.56 %, 28.12 %, 20.80 %,	Air-driven fluidized-bed NTP	Efficient soil degradation/defluorination; enhanced plasma–	Laboratory-scale; soil-dependent; selected	TRL 3-4	Not reported; moderate-high	Soil	[269]

PFHxA, PFPeA	14.90 %, and 5.90 % defluorination within 100 mins		soil contact; chemical-free; minimal secondary waste	PFAS; scale-up and costs unverified		(improved plasma efficiency)	
PFOS	76.16 % degradation and 21.08 % defluorination	Iron-based mineral-mediated photocatalytic reduction (surface-bound Fe(II))	Efficient degradation/defluorination; enhanced electron transfer; Fe(II)-mediated C-F cleavage; sustainable catalyst	Laboratory-scale; PFOS only; light-dependent; limited real-water validation; scale-up required	TRL 2-3	Not reported	Aquatic environment [297]
PFBS, PFHxS, PFOS, PFOSA	PFBS: 41.6% removal/40.3% defluorination; PFHxS: 66.8% removal/55.5% defluorination; PFOS: 98.5% removal/40.3% defluorination; PFOSA: 81.3% removal/58.6% defluorination	Chitosan-modified biochar coupled with UV/sulfite advanced reduction	Adsorption-hydrated electron synergy; enhanced degradation; broad PFAS applicability; low-cost biochar; robust	Laboratory-scale; UV/sulfite required; water chemistry-dependent; scale-up required	TRL 3-4	Not reported; moderate (UV-driven)	Aquatic environment [298]
PFOA	90.0 % degradation and 49.8 % defluorination within 1 min	Copper-doped nanoscale zero-valent iron (Cu-nZVI) synergistic enrichment–oxidation	Adsorption-oxidation synergy; deep defluorination; enhanced electron transfer; effective in environmental matrices	Laboratory-scale; PFOA only; catalyst stability unverified; scale-up required	TRL 3-4	Not reported; suggests low-moderate (Cu-nZVI)	complex water matrices [291]
PFOA	99% degradation and 64.8% defluorination under oxic conditions, within 24 h	Sulfur vacancy-engineered $ZnIn_2S_4$ photocatalysis (singlet oxygen-mediated)	Visible-light degradation; $^1O_2$ mediated defluorination; reusable catalyst	Laboratory-scale; selected PFAS; scale-up required	TRL 2-3	Not reported; suggests low-moderate (visible light)	Aquatic environment [265]
PFOA	≈54% defluorination	Regenerable adsorption-electrochemical	Rapid PFAS capture; integrated adsorption/mineralization; regenerable	Laboratory-scale; limited continuous validation; complex-water performance	TRL 3-4	Not reported; suggests low (integrated capture/mineralization)	Aquatic environment [277]

		mineralization platform	adsorbent; broad PFAS applicability; minimal waste	unverified; scale-up required				
PFOA	85.2 % degradation and 63.1 % defluorination within 24 h	Self-regenerable Zeolite Beta (35) adsorption–photocatalysis	Adsorption-photocatalysis; solar-driven; self-regenerating; reusable; minimal waste	Laboratory-scale; PFOA only; limited real-water validation; scale-up required	TRL 3-4	Not reported; suggests low (solar-driven)	Aquatic environment	[289]
GenX, PFOA	GenX removal rates of 0-57 % and PFOA removal of 31-98 %, with better performance in treated wastewater. In model solutions, 100 % total defluorination was achieved	Iodide-assisted UV/sulfite advanced reduction process (UV/sulfite/I^-)	Enhanced GenX degradation/defluorination; hydrated electrons; improved kinetics; effective in wastewater	Laboratory-scale; UV/sulfite/iodide required; wastewater-dependent; scale-up required	TRL 3-4	Not reported-suggests Moderate (UV-driven; iodide improves efficiency)	Aquatic environment	[299]
PFOS	degradation rate of 96.6 % and a defluorination rate of 68.6 % within 30 min at an input power of 50 W	Bi_2O_3-assisted dielectric barrier discharge (DBD) plasma	Plasma-enhanced degradation; improved C-F cleavage/defluorination; reusable catalyst; minimal reagents	Laboratory-scale; PFOS only; plasma required; scale-up required	TRL 2-3	Not reported-suggests Moderate-High (Energy-intensive plasma proces)	Aquatic environment	[267]
PFOA, PFOS	nZVI/rGO achieved rapid adsorption (98.2% PFOA, 97.6% PFOS) and defluorination (64.2% PFOA, 57.8% PFOS) within 72 h	nZVI/rGO sequential adsorption-photocatalytic degradation	Adsorption-photocatalysis; enhanced electron transfer; reusable catalyst; minimal waste	Laboratory-scale; selected PFAS; light-dependent; catalyst stability unverified; scale-up required	TRL 3-4	Not reported- suggests Low-Moderate	Aquatic environment	[275]
PFOA	98% removal efficiency, and partially defluorinated into zinc fluoride after 24 h	PFAS sorption and utilization in rechargeable zinc-ion batteries	PFAS removal and valorization; resource recovery; reusable electrodes; minimal secondary waste	PFAS capture only; no mineralization; scale-up required;	TRL 2-3	Not reported-suggests Low (Adsorption-based; low energy demand)	Aquatic environment	[300]

PFOA, PFOS, 6:2 FTS	~82% PFAS removal in groundwater; complete defluorination in MQ/creek water, but lower in seawater (72–81%)	Ultrasonication (sonochemical degradation)	Chemical-free degradation; cavitation-driven pyrolysis/radicals; water chemistry evaluation; minimal waste	Laboratory-scale; water chemistry-dependent; scale-up and costs unverified	TRL 3-4	Not reported; suggests high (ultrasonication)	Aquatic environment	[301]
PFOA, PFCAs, FTCAs	96 % defluorination of PFOA within 240 min at pH 10; Across diverse water matrices (e.g., tap water or lake water), the system maintained >70 % defluorination efficiency	UV/sulfite reduction–oxidation coupling (hydrated electrons + reactive bromine species)	Simultaneous PFAS defluorination/bromate detoxification; hydrated electron-driven CF cleavage; self-sustaining redox cycle; applicable to bromide-rich waters	Laboratory-scale; UV/sulfite required; bromide-dependent; scale-up required	TRL 3-4	Not reported; suggests moderate (UV-driven)	Aquatic environment	[303]
PFCA, PFOA, PFOS	reduction of PFOA in its concentration by 45.6 ± 1.8; 30–40% PFOA removal rates by oven-dried killed fungal-wood sawdust material	Fungal biodegradation (wood-decomposer fungi)	Low-energy bioremediation; biological defluorination; chemical-free; potential for in situ treatment	Slow degradation; selected PFCAs; laboratory-scale; incomplete mineralization; field validation needed	TRL 2-3	Not reported; suggests very low (fungal metabolism)	-	[279]
PFOA	91.6 % degradation rate, >90 defluorination of PFOA within 8 h of ball milling	Mechanochemical degradation using waste heating pad material (ball milling)	Waste-to-resource mechanochemical treatment; efficient PFOA degradation/defluorination; solvent-free; low chemical use	Laboratory-scale; PFOA only; milling optimization required; scale-up challenging	TRL 2-3	Not reported; suggests moderate (mechanochemical milling)	-	[273]
PFAS	90% removal	Selective adsorption using fluorous active sites	Selective PFAS adsorption; efficient desorption/regeneration; reduced waste; reusable adsorbent	PFAS capture only; no degradation; laboratory-scale; long-term stability and scale-up unverified	TRL 3-4	Not reported; suggests low (adsorption-based)	Aquatic environment	[274]

PFOA, PFOS	HTL removed parent PFAS without defluorination; hydrochar/KOH enhanced defluorination to 100% PFOA and 95% PFOS	Catalyzed hydrothermal liquefaction using modified hydrochar	Hydrochar-enhanced PFAS destruction/defluorination; effective for PFOA/PFOS; sludge-derived catalyst; waste valorization	High-temperature HTL; laboratory-scale; hydrochar stability and scale-up unverified	TRL 3-4	Moderate; 266–232 kJ mg^{-1} PFAS with KOH optimization	Aquatic environment	[304]
PFOA	87.9 % removal and 42.5 % defluorination of a 10 mg/L PFOA solution within 5 h; The cathode maintains >80 % efficiency, 42.5 % defluorination within 5h across pH 3–11 over five cycles	Non-noble-metal electrocatalytic reduction (PEI-GO/Co-NG cathode)	Low-cost non-noble catalyst; enhanced adsorption/C–F cleavage; high PFOA removal and defluorination; stable across diverse waters; reusable	PFOA-focused; incomplete defluorination; laboratory-scale; long-term durability and scale-up unverified	TRL 3-4	Not reported; low-moderate (low potential due to low voltage/non-noble cathode)	Aquatic environment	[285]
PFOA, PFOS	PFOA: 97.1% removal and 86.6% defluorination; PFOS: 99.7% removal with 48.5% defluorination within 10 min	Piezoelectric direct discharge plasma (plasma-liquid interfacial F/OH exchange)	Plasma-liquid interfacial degradation; enhanced reactive species/C–F cleavage; chemical-free operation; sustainable PFAS destruction	Laboratory-scale; selected PFAS; water chemistry-dependent; scale-up required	TRL 2-3	Not reported; moderate-high (plasma-driven)	Aquatic environment	[286]
148 PFAS	>99.9% removal, near complete defluorination within 90 min	Hydrothermal alkaline treatment	Broad-spectrum PFAS destruction; extensive defluorination/mineralization; applicable to water and soil; minimal by-products	High-temperature/pressure alkaline conditions; equipment-intensive; pilot-scale; cost and scale-up challenges	TRL 4-5	Not reported; suggests high (hydrothermal conditions)	Groundwate, soil from aqueous film-forming foam impacted sites	[152]
GenX	>95% of GenX removal in 9 minutes, ~100%	redox-copolymer, poly(4-	High adsorption capacity; reversible		TRL 3-4	Low-Moderate; operates at low	Groundwater,	[305]

	defluorination after 24 hours	methacryloyloxy-2,2,6,6-tetramethylpiperidin-1-oxyl-*co*-4-methacryloyloxy-2,2,6,6-tetramethylpiperidine) coupled with a boron-doped diamond counter electrode	electro-regeneration; broad pH/water compatibility; flow-cell scalability; integrated defluorination	Laboratory-scale only; mainly tested on GenX; full mineralization, scalability, stability, and cost remain uncertain		potential (0.8 V) and enhances efficiency by PFAS concentration before destruction	drinking water	
PFOA, PFOS	PFOA : 51.7%, PFOS : 33% degradation; PFOA: 44.7%; PFOS: 23% defluorination	Electrochemical destruction and electromigration in saturated soil	In situ PFAS mobilization and degradation; effective for PFOA/PFOS defluorination at low voltage (24 V) with no short-chain intermediates detected	Lab-scale soil column; PFOS recalcitrant; incomplete mineralization; 10-day treatment; field validation and cost assessment needed	TRL 4	No report-suggests Moderate. Operated under a relatively low applied voltage (24 V; 467–690 mA),	Soil	[306]
PFCAs, GenX	PFOA: 82%, PFOS: 65% for and defluorination at pH 12; Defluorination rates varied between 0.0003 and 0.1604 min^{-1}	Medium-pressure UV/sulfite advanced reduction process (MP-UV/sulfite	Rapid defluorination of 22 PFAS via enhanced hydrated electrons; effective for legacy/emerging PFAS with broad applicability and reduced O_2/pH sensitivity	Lab-scale only; requires pH ≈12 and sulfite; reduced efficiency in real waters; poor UV energy utilization; scale-up needed	TRL 3-4	Not reported-suggests High; ~97% UV energy loss limits efficiency despite rapid defluorination	Groundwater	[307]
FTCA, FTSA, PFCA, and PFSA	97–103% defluorination	Integrated oxidation-reduction (HO• oxidation + UV/sulfite reduction)	Near-quantitative defluorination of diverse PFAS; combines oxidation and hydrated electrons for C–F	Lab-scale only; requires sequential redox steps (UV/sulfite); PFAS-dependent efficiency; scalability and cost remain uncertain	TRL 3-4	Not reported-suggests Moderate. Higher energy demand due to UV irradiation and chemical reagents	Aquatic environment	[308]

			cleavage with minimal intermediates					
PFOA, PFOS	PFOA: 99%; PFOS: 98% removal within 4 h; complete defluorination	Mechanochemical remediation (planetary ball milling)	Effective soil PFAS destruction via solvent-free mechanochemical defluorination; minimal waste, on-site potential	Lab-scale only; prolonged milling and equipment requirements limit scalability	TRL 3-4	Not reported-suggests Moderate-High. High energy demand due to prolonged mechanical milling	Soil	[272]
PFAS	100% defluorination at the end of 2 h	Hybrid UV/electrochemical reduction (hydrated electron-mediated)	Effective PFAS defluorination via hydrated electrons; improved degradation through combined photoelectrochemical reduction	Lab-scale study; PFAS-dependent efficiency; requires UV/electrochemical systems; real-water and scale-up validation needed	TRL 2-3	Not reported-suggests Moderate-High. Higher energy demand due to combined UV and electrochemical inputs	Aquatic environment	[150]
PFOA	93% reduction in < 24 hours; 75% defluorination using 50 mA/cm^2	Electrochemical oxidation using BDD with combined current density	High degradation/defluorination; optimized current density reduces energy; BDD enables rapid PFAS treatment	Lab-scale only; mainly PFOA; BDD cost and water matrix effects limit scale-up	TRL 4-5	Not reported-suggests Moderate. Reduced energy consumption via optimized current density	Aquatic environment	[321]
15 PFASs	PFOA: 93%, PFOS: 98% defluorination; >99% degradation of PFOA was observed in the single-solute experiment after 49 h	UV/sulfite photoreductive treatment (hydrated electron-based)	PFAS destruction in AFFF matrices via hydrated electrons; limited intermediates	Lab-scale; requires UV/sulfite and pH ~12; oxygen sensitivity; incomplete mineralization; scale-up challenges	TRL 3-4	Not reported-suggests moderate (UV-driven)	Aquatic environment	[302]
PFOS	~86% removal, ~24% defluorination after 2 h	Electrochemical reductive defluorination (potential-driven electron transfer)	Cathodic potential enhances PFOS defluorination via electron transfer; chemical-free electrocatalytic destruction	Lab-scale PFOS study; incomplete defluorination; mixed PFAS and scale-up not evaluated	TRL 2-3	Not reported-suggests moderate. Requires continuous electrical input	Aquatic environment	[309]

34 PFAS	TFA: 100% defluorination; ~67% overall deF% at 48 h	Hydrated electron-mediated reductive defluorination	Broad PFAS degradation; extensive C–F cleavage with limited intermediates	Lab-scale; requires hydrated electron generation and alkaline/O_2-free conditions; scalability unverified	TRL 2-3	Not reported-suggests moderate. Mechanistic hydrated electron defluorination study	-	[120]
PFOS	85.5% defluorination after 120 h	Electrocatalytic defluorination using industrial thermoelement materials	Low-cost thermoelectric catalysts enable electrocatalytic PFOS defluorination via electron transfer	Lab-scale PFOS study; incomplete defluorination; durability, mixed PFAS, and scale-up unverified	TRL 2-3	Not reported-suggests moderate. Requires continuous electrical input	Aquatic environment	[310]
PFOA,	nearly complete degradation, 93.4 % removal and 91.5 % defluorination effi ciency in 1 h	PTFE piezocatalytic degradation	PTFE-derived mechanocatalyst enables PFAS degradation without UV/electrical inputs; low-carbon C-F cleavage	Lab-scale only; stability, mineralization, and scalability require validation	TRL 2-3	Not reported-suggests Low-moderate. Lower energy; no UV/electrochemical input	Aquatic environment	[311]
PFOA	60 % of the degradation	Pulsed volume DBD plasma	Plasma-driven PFAS degradation via reactive species; no chemical additives; promotes C-F cleavage	Lab-scale only; parameter-dependent efficiency; energy losses and scale-up challenges	TRL 3-4	Not reported-suggests moderate-high. High energy demand; pulse optimization improves efficiency	Aquatic environment	[312]
PFOA	94.0 % degradation 73.0 % defluorination	CeO_2 electrode-enabled low-potential electrochemical oxidation (adsorption–activation strategy)	Lower-energy PFAS oxidation; CeO_2 enhances adsorption/activation; avoids noble metals	Lab-scale only; CeO_2 stability, complex matrices, and scale-up require validation	TRL 3-4	Not reported-suggests Low-Moderate. Lower oxidation potential reduces energy demand	Aquatic environment	[263]
PFOA, PFOS, PFAS	~100 % removal, PFOA: 60.4 % and PFOS: 33.1 % defluorination in 2 h at	Persulfate-activated electrochemical	Enhanced PFAS degradation via BDD •OH and persulfate	Lab-scale; persulfate cost, BDD expense, and scale-up challenges	TRL 3-4	Not reported- suggests Moderate-High. Energy demand	Aquatic environment	[127]

	pH 3.8–13; >100 % defluorination for 28 PFAS	oxidation using BDD anode	radicals; stable electrode with broad applicability			depends on current density and treatment time.		
PTFE	~32 % defluorination within 9 h	High-frequency ultrasonication degradation of PTFE micro/nanoplastics	Cavitation-driven fluoropolymer degradation; no oxidants/catalysts required	Not direct PFAS treatment; PTFE-focused; energy-intensive and lab-scale	TRL 2-3	Not reported-suggests High. High energy demand due to inefficient acoustic conversion	Aquatic environment	[314]
PFAS	~90% removal, 76-100% defluorination	Integrated redox-electrodialysis-electrosorption	Broad PFAS removal; selective electrochemical capture with regeneration and low waste	Removes but does not destroy PFAS; membrane fouling, cost, and scale-up challenges	TRL 4-5	Not reported-suggests Low-Moderate. Low-energy electrosorption via ion transport	Aquatic environment	[315]
PFOS	> 99 % removal within 0.5 h, < 10 % defluorination; > 85 % of defluorination was achieved in the unbuffered indole reactor	Gas-sparging assisted UV–indole reductive treatment	PFOS reductive degradation via enhanced hydrated electrons; recyclable indole mediator	Lab-scale PFOS study; requires UV/mediator; stability, matrices, and scale-up uncertainn	TRL 3-4	Not reported -suggests Moderate. Energy demand from UV/gas sparging; improved electron use lowers waste	Aquatic environment	[316]
PFOS, PFOA, PFDA	PFOS (94%), PFOA (89%), and PFDA (60%) after 1 day at 70 °C	Soluble metal porphyrin–zero-valent zinc (Zn^0) reductive defluorination	Metal porphyrin/Zn^0 enables mild, energy-free reductive defluorination of branched PFAS	Zn^0 consumption, by-products, recovery, and scale-up remain challenges	TRL 2-3	Not reported-suggests Very Low-Low. No external energy; demand from Zn^0 production and handling	Aquatic environment	[317]
PFOA	99.5% removal, 70% defluorination in 3 h at a pH 4.5	UiO-66 modified boron nitride electrocatalytic degradation (“Trap-n-Zap”)	UiO-66 enriches PFOA for single-step adsorption/electrochemical destruction at low concentrations	Lab-scale PFOA study; MOF stability, cost, competition, and scale-up challenges	TRL 3-4	Not reported-suggests Low-Moderate. Trap-and-zap enrichment reduces energy demand for dilute PFOA treatment		[323]

PFOA	complete degradation and 94.7 % defluorination	UV/sulfur-based advanced reduction processes (UV/sulfite and related systems)	PFOA degradation in real wastewater via hydrated electrons; evaluates operational and matrix effects	Requires UV/sulfur reagents; matrix effects, PFOA focus, and scale-up challenges.	TRL 3-4	Not reported-suggests Moderate. Energy demand mainly from UV irradiation; reagent optimization improves efficiency	Aquatic environment	[318]
PFOS, PFOA, and 6:2 FTS, PFBS	100 % degradation and > 90 % defluorination, >99.9 % of PFOS, PFOA, and 6:2 FTS, destruction and complete quantitative defluorination of PFBS	Optimized UV/sulfite/iodide advanced reduction process	Near-complete PFAS destruction via iodide-enhanced hydrated electrons; high fluoride recovery	Requires UV/sulfite/iodide; chemical cost, alkaline conditions, and scale-up challenges	TRL 3-4	Not reported-suggest Moderate-High. High energy demand due to continuous UV irradiation	Aquatic matrices	[313]
PFOA	~100% degradation, 55% degradation in the presence of 5 mM carbonate within 1 h; defluorination from nearly 90% (0 mM) to ~60% (5 mM) after 24 h	Hydrated electron-mediated treatment (UV/sulfite advanced reduction process)	Hydrated electron defluorination; reveals water chemistry effects and UV/sulfite optimization	Mechanistic study; requires UV/sulfite; matrix effects and scale-up challenges	TRL 2-3	Not reported; suggests Moderate. Energy demand depends on hydrated electron generation method)	Aquatic environment	[319]
(E)-perfluoro-(4-methylpent-2-enoic acid) (PFMeUPA)	99.81% removal, 78.67% defluorination	Quaternary ammonium surfactant-modified cathode for direct electroreductive defluorination	Cathodic reduction of unsaturated PFAS; quaternary ammonium enhances PFAS enrichment and electron transfer	Lab-scale unsaturated PFAS study; cathode stability, matrix effects, and scale-up unresolved	TRL 2-3	Not reported-suggests Low-Moderate. Lower energy demand; avoids oxidants and UV irradiation	groundwater	[262]
PFOA	100% removal, 83.1% defluorination after 24 h	Aminated biosorbent coupled with UV/sulfite photocatalytic	Integrated PFOA capture–destruction; aminated biosorbent concentrates PFAS for	Multi-step UV/sulfite process; regeneration, stability, cost, and scale-up challenges	TRL 3-4	Not reported-suggests Moderate. Energy demand mainly from UV irradiation	Aquatic environment	[276]

		reduction (adsorption-desorption-destruction)	UV/sulfite defluorination and reuse				
PFOS	complete defluorination	Nonprecious [NiFe]-LDH electrocatalytic defluorination with pulsed electrolysis and UV assistance	Complete PFOS defluorination; non-noble catalyst and pulsed electrolysis improve efficiency	Requires alkaline electrolyte/UV; lab-scale, durability, and fluoride management challenges	TRL 3-4	Not reported-suggests Moderate. Pulsed electrolysis lowers energy demand; UV adds energy input	Aquatic environment [322]
PFOS, PFOA, GenX, PFBS	PFOS: 81.4%, PFOA: 77.8%, GenX: 66.6%, PFBS: 13.2% defluorination	UV/sulfite hydrated electron-mediated reductive degradation with HRMS-based transformation assessment	Pulsed electrolysis lowers energy demand; UV adds energy input	Mechanistic study; incomplete mineralization/intermediates; requires UV/sulfite	TRL 3-4	Not reported-suggests Moderate. Energy demand mainly from UV-driven hydrated electron generation	Aquatic environment [292]
FHxS, PFPeS, PFBS, PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFOS, 4:2 FTS, 6:2 FTS	>99% for destruction within 10 mins, and 1.6 mins for PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFOS, 4:2 FTS, 6:2 FTS	Continuous HALT	Continuous-flow hydrothermal treatment enables PFAS destruction and defluorination in real AFFF water	High temperature/pressure/alkali; costly reactors, corrosion, and energy demand	TRL 5-6	Not reported- suggests High. Energy demand from hydrothermal heating and pressure maintenance	liquid matrices [271]
PFOA	> 99% degradation, 57.6% defluorination within 180 min	Photo-induced SFLP photocatalysis	SFLPs enrich PFOA and enhance photocatalytic	Lab-scale PFOA study; UV demand, catalyst	TRL 2-3	Not reported-suggests Moderate. Energy	Aquatic environment [281]

		using defect-engineered $Bi_3O(OH)(PO_4)_2$	defluorination without oxidants	stability, matrix effects, and scale-up challenges		demand mainly from UV irradiation		
GenX	>80% degradation within 1 h, no defluorination detected	Ultrasonic irradiation (sonochemical degradation)	GenX degradation via cavitation-induced pyrolysis with fluoride release; no chemical additives	High ultrasonic energy demand; lab-scale, reactor, and scalability challenges	TRL 3-4	Not reported-suggests High. High-frequency ultrasound is energy-intensive; suited for concentrated PFAS streams	Aquatic environment	[287]
PFOS, PFOA	60.4% removal (30.2% lower than control	Electron shuttle-enhanced Fe(III) reduction for PFAS remediation in wetland sediments	Microbial Fe(III) reduction enhanced by electron shuttles enables low-energy in situ PFAS removal	Sediment-based removal; slow mineralization, matrix dependence, and uncertain scalability	TRL 2–3	Not reported-suggests Very Low. Low energy demand; mainly from electron shuttle production/application	Wetland sediment	[283]
PFOS, PFHpS, PFOA	99.999 % destruction of all PFAS at T = 410 – 650 °C, complete PFOS defluorination at T = 650 °C at residence time of ~ 30 s	Continuous SCWO	High-temperature continuous-flow treatment achieves rapid PFAS destruction and defluorination	High temperature/pressure; costly reactors, fouling, and pre-concentration needs	TRL 5-6	Nreported-suggests High. High energy demand to maintain supercritical conditions	Aquatic environment	[270]
PFAAs, PFOS, PFCAs, PFSAs	~ 8% defluorination of PFAAs	nNiFe-activated carbon (nNiFe-AC) nanocomposite under steady-state flow	Integrated PFAS adsorption–reduction; continuous-flow treatment with enhanced PFOS transformation	Partial defluorination; bicarbonate effects, heating, and long-term stability challenges	TRL 3-4	Not reported-suggests Low-Moderate. Low energy demand; mainly for mild heating (50-60 °C)	groundwater	[320]

TRL= Technology Readiness Level. TRL 2–3 =laboratory proof-of-concept; 3-4 = laboratory validation; **4-5** =advanced laboratory validation; **5-6** =pilot-scale continuous reactor validation; TRL values were assigned by the authors based on the NASA/European Commission TRL framework using the maturity of the technology reported in each study (laboratory validation, relevant-environment testing, pilot-scale demonstration, and commercial deployment) [343–346]. These values are interpretative assessments and were not necessarily reported by the original publications; BDD= Boron-Doped Diamond; DBD= dielectric barrier discharge; SCWO= Supercritical Water Oxidation; NTP= non-thermal plasma; SFLP= Induced surface frustrated Lewis pair; CEC= Contact-electro-catalysis; ADRP= Adsorption-regeneration-distillation-plasma

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