



Table 12-1. LIQUID TECHNOLOGIES—REMEDIATION TECHNOLOGIES AND METHODS COMPARISON


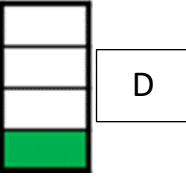
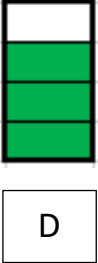

This table belongs with the ITRC PFAS Tech Reg Document. The ITRC intends to update this table periodically as new information is gathered. This table has been updated (October 2021) to add a selection of new technologies and new references for some of the technologies presented in the April 2020 table version. The user should note that these additional references have transformed the third column into a selection of representative technologies of likely interest, and not a complete review of all of the references. The expanded body of research has made it too cumbersome to succinctly capture the PFAS and concentrations that were investigated for each reference and what removal efficiency was achieved. Many of these studies were novel at the time of original publication of this table and providing the PFAS and range of concentrations for the body of research was instructive at that time. The user should consult the references directly for additional information on the PFAS and concentrations that were researched.



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Users who identify updates to the material in this table are encouraged to send that information to itrc@itrcweb.org


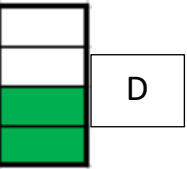
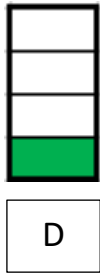
The mechanism of treatment (separation vs. transformation) is listed under each Remediation Technology group.

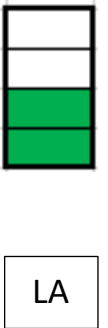

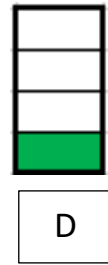
Remediation Technology Group	Remediation Technology (Includes PFAS-1 document section number for more information)	Chemicals Evaluated and Reported Removal Efficiencies for Select Studies	Strengths (Includes Co-Contaminants, Sustainability, Scalability)	Challenges/Limitations (Includes Co-Contaminants, Sustainability, Scalability)	Waste Management/Life Cycle	Future Data Needs	PFAS Demonstration Maturity (FI – Field Implemented, LA – Limited Application, D – Developing)	References
12.5.2 Flocculation/Coagulation (Separation)	12.5.2 Alum	PFOA/PFOS ~1,000 µg/L, between 1–20% removal based on coagulant dosage PFOA~8 µg/L, 20% removal PFOS~236 µg/L, 40% removal	Conventional technology. Used commonly for water treatment in other applications. Readily scalable.	Current data show that alum is <i>not effective for meeting health advisory</i> (low ng/L). May best serve as initial treatment technology. Will likely require polishing.	Requires solids dewatering and disposal.	Permanence of separation is unknown. Data from a wider variety of site conditions/water types. Data as combined approach with other "polishing technologies." Data to understand efficiency at lower initial concentrations (ng/L level).		Bao et al. 2014; CH2M 2017
	Polyaluminum chlorides	PFOA~50–3,000 µg/L; 1 µg/L; 99% removal observed PFOA/PFOS~1,000 µg/L, 1–25% removal based on coagulant dosage	Conventional technology. Used commonly for water treatment in other applications. Readily scalable.	Will likely require polishing.	Requires solids dewatering and disposal.	Permanence of sequestration is unknown. Data from a wider variety of site conditions/water types. Data as combined approach with other "polishing technologies." Data to understand efficiency at lower initial concentrations (ng/L level).		Deng et al. 2011; Bao et al. 2014

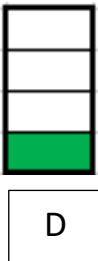
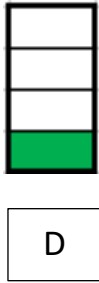
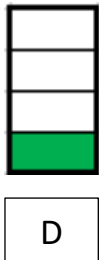
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	Ferric salts	PFOA/PFOS~1,000 µg/L, 1–50% removal based on coagulant dosage; removal improved to 48–95% at pH 4; PFOA~8 µg/L, 15% removal PFOS~236 µg/L, 30% removal	Conventional technology. Used commonly for water treatment in other applications. Readily scalable.	Current data show that ferric salts are not effective for meeting health advisory (low ng/L). May be best served as initial treatment technology. Will likely require polishing.	Requires solids dewatering and disposal.	Data from a wider variety of site conditions/water types. Data as combined approach with other "polishing technologies." Data to understand efficiency at lower initial concentrations (ng/L level).		Bao et al. 2014; CH2M 2017
	Covalent bound hybrid coagulants	PFOA ~100 µg/L, 99% removal	99.6% removal of PFOA was observed with test conditions.	Unproven outside lab in deionized water. Commercial availability and scalability of polymer production is unknown.	Requires solids dewatering and disposal of PFOA-containing sludge.	Permanence of separation is unknown. Further R&D needed. Scalability and efficiency at scaled-up level not known.		Zhao et al. 2016
	Specialty coagulants	PFAS~380–480 µg/L, 87–98% removal PFOA~8 µg/L, 20% removal PFOS~236 µg/L, 80% removal	Application of coagulation in conventional water treatment equipment is well known. Readily scalable.	Limited data on performance of specialty coagulants.	Requires solids dewatering and disposal.	Scale-up data for larger applications. Permanence of separation is unknown. Data from a wider variety of site conditions/water types. Data as combined approach with other "polishing technologies." Data to understand efficiency at lower initial concentrations (ng/L level).		CH2M 2017; Birk and Alden 2017
	Polymeric coagulant	Polydiallyldimethylammonium chloride (polyDADMAC) increased the sorption coefficient of PFAS by as much as a full order of magnitude. PFOS; PFOA; PFNA; PFHxS; PFHpA; and PFBS.	Application of polymeric coagulants polyDADMAC and in combination with powdered activated carbon (PAC) to increase soil organic content.	In situ treatment of groundwater with injection to create permeable absorptive barrier (PAB) or treatment volume of either polyDADMAC or polyDADMAC+PAC using alginate beads, osmotic pumps, and commercially available floc log and coagulant and PAC.	None, in situ treatment of groundwater.	Field demonstration needs to be done		Aly et al. 2018; Anderson et al. 2019; Simcik 2019



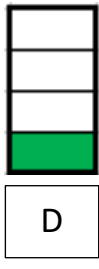
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				Data showed as much as 4,100 pore volumes of PFAS for a soil at 100 parts per billion before breakthrough would occur.				
	Electrocoagulation	PFOA~1,000–100,000 µg/L, up to 99% removal; removal depends on cathode and anode chosen, other anions present in solution, etc.	Can be improved by increasing current and decreasing pH. Improved by addition of H ₂ O ₂ to promote advanced oxidation. Research shows zinc hydroxide electrode may have better performance.	Best results have high energy consumption.	Requires solids dewatering and disposal.	Data as combined approach with other "polishing technologies." Permanence of separation is unknown. Scale-up data for larger applications. Data from a wider variety of site conditions/water types. Data to understand efficiency at lower initial concentrations (ng/L level).		Yang et al. 2016; Lin et al. 2015; Wang et al. 2016b
Sorption (Separation)	12.2.1.1 Granular activated carbon (GAC)	Demonstrated for all PFAS tested to date at parts per trillion to parts per billion concentrations for aboveground activated carbon treatment	Treats all tested PFAS to date with high removals prior to breakthrough. Design flexibility to increase removal. Simple to operate. Multiple vendors. Off-site reactivation/regeneration available for PFAS.	Possible faster breakthrough times for shorter chain versus longer chain PFAS under certain influent and other conditions. Becomes less economical at higher influent concentrations (for example, >10–100 ppb). Competitive adsorption w/ other species. Precursors and other PFAS not analyzed for can increase GAC loading and accelerate changeout frequencies. No destruction of PFAS, unless it is reactivated or incinerated at high temperature (>1,100°C). <i>Pretreatment may be necessary.</i>	Spent activated carbon must be removed for offsite disposal, or reactivation/regeneration.	More comprehensive shorter chain adsorption capacity data. Competition with other contaminants and aqueous species. Regulation of individual PFAS in addition to PFOA and PFOS. Impact on PFAS precursors.		Dickenson and Higgins 2016; Brewer 2017; Cummings et al. 2015; Appleman et al. 2013; Szabo et al. 2017; Burdick et al. 2016; Woodard, Berry, and Newman 2017; Hohenstein 2016; Xiao et al. 2017; AWWA 2016; Mimna 2017; McNamara et al. 2018; Westreich et al. 2018; Liu, Werner, and Bellona 2019; Call 2021



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	Carbon nanotubes (CNT)/modified CNT and graphene	PFOA, PFOS	Co-contaminants are remediated. Very high relative surface area (100 times higher than GAC), can be modified with positive charges.	Surface area may become clogged by organic carbon in soil. Expensive to manufacture (currently).	Unknown	Understanding long-term stability of contaminant. Demonstrate adsorption capacity versus cost.		Chen et al. 2011; Li et al. 2011; Kwadijk, Velzeboer, and Koelmans 2013; Lath et al. 2018; Zhao 2020
	12.5.1.1 Colloidal activated carbon (in situ treatment)	Demonstrated full-scale on broad range of PFAS contaminants	Applied to eliminate migration and potential exposure to PFAS. Carbon suspension flows into aquifer coating matrix. PFAS is immobilized onto aquifer matrix. No operation and maintenance. No waste generated. Longevity projected to be multiple decades with single injection. If required, can be reapplied. Highly sustainable with very low carbon footprint.	PFAS contaminants are immobilized, not destroyed. Certain co-contaminants may reduce efficacy.	No waste generated.	Limited number of full-scale applications to date. Need documentation of longevity.		McGregor 2018; Carey et al. 2019

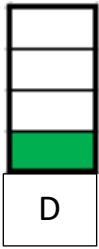
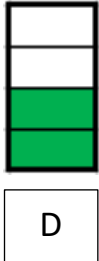
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	12.2.1.2 Anionic exchange resins (AEX or IX)	Demonstrated for all PFAS tested to date at parts per trillion to parts per billion concentrations for aboveground anionic exchange resins. Shorter chain PFAS break through faster. Low or high concentration for single use nonregenerable resin; high concentration for regenerable resin.	Higher loading capacity for PFAS versus activated carbon at equivalent influent concentrations and other operating conditions based on a few comparison column and pilot studies. Design flexibility to increase removal. Simple to operate without regeneration. On-site solvent-brine regeneration is currently commercially available from one vendor for its resin designed for PFOA/PFOS removal.	Possible faster breakthrough times for shorter chain versus longer chain PFAS under certain influent and other conditions. Virgin media costs twice as much as activated carbon, but less media replacement is needed. Removal efficiencies are compound specific. Payback for on-site regeneration may be long, but can become more economical versus off-site reactivation of activated carbon at higher influent concentrations of PFAS (for example, >10–100 ppb) because of the higher loading capacity for the anionic resins. Competitive removal with other ions. No destruction of PFAS, unless it is incinerated at high temperature (>1,100°C).	Spent resin must be removed for off-site disposal or on-site regeneration. Solvent-brine, which is flammable, is only demonstrated solution for on-site regeneration. Onsite destruction technologies for concentrated regeneration brine are currently under development.	Full-scale operation experience. Similar future data needs as activated carbon. Improve cost-benefit analysis to compare single use, regenerable, and combined use ion exchange resin approaches to address mixed PFAS.		Deng et al. 2010; Appleman et al. 2014; Du et al. 2014; Dudley, Arevalo, and Knappe 2015; Woodard, Berry, and Newman 2017; McCleaf et al. 2017
	12.5.1.4 Biochar	Treatment appears to be demonstrated for all PFAS tested to date. Most effective for longer chain PFAS.	Possible alternative to GAC. Effectiveness increases with surface area.	Only proven effective on ultrapure water. Natural organic matter reduces effectiveness. Slow reaction kinetics.	Off-site disposal required for spent biochar.	More column/pilot studies. Full-scale operation experience to identify limitations. Similar future data needs as activated carbon.		Xiao et al. 2017; Rahman et al. 2014
	12.5.1.3 Zeolites (natural and modified)	PFOS~2,900–4,000 ng/L with 81– >99% removal	Usually has sorption capacity less than GAC. Would be effective on some organic co-contaminants. Inexpensive mined product.	May react differently with short-chain PFAS or carboxylates (only tested on sulfonates). Is a sequestration technology and not a destructive one. The surface area is relatively low compared to activated carbon and specialized minerals (e.g., aluminum hydroxide has a surface area ~10 m ² /g; pseudoboehmite in RemBind® has a surface area of 250 m ² /g).	Waste adsorbent needs disposal.	Assessment on a broader suite of PFAS of differing chain lengths. Full-scale operation data		Ochoa-Herrera and Sierra-Alvarez 2008; Chiang et al. 2017; Dong 2020




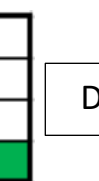
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	Surface-modified clay	86% removal of 65 ug/L total PFAS (13 PFAS) 96% removal 15 ug/L PFOS 90% removal 6 ug/L PFOA Pilot column: Treated influent PFOA (16 ng/L) and PFOS (23 ng/L) to <2 ng/L for 8.7 months. Two studies summarize Rapid Small Scale Column Testing (RSSCT) of surface-modified clay.	High affinity for a variety of PFAS. Resistant to the impacts of dissolved organic carbon (DOC) and co-contaminants. Commercially available media.	Does not remove other soluble co-contaminants.	Spent media must be disposed of through incineration or landfilling.	Media regeneration potential. Engineering parameters for full-scale filtration systems.		Yan et al. 2020; Yan, Wang, and Liu 2021; Pannu and Plumlee 2021; Hwang and Grieco 2021; Grieco et al. 2021; Najm et al. 2021.
	12.5.1.2 Coated sand	PFOA and PFOS	May remove other co-contaminants at same time.	Field demonstration needed.	Can be regenerated up to 10 times before spent material must be removed for off-site disposal.	Permanence of separation unknown		Badruddoza, Bhattarai, and Suri 2017
	Protein sorbents	PFOS, PFNA, PFOA PFHxS, PFHxA, PFHpA, PFBS, and PFBA	Initial results suggested proteins could be effective filter media with measured k_d values for various protein sorbents.	Research and development to define kinetics of sorption, methods for regeneration of protein sorbents, and design of protein-sorbent filters.	Regeneration testing ongoing. Preliminary results suggest heating for desorption denatures proteins, inactivating them.	Additional studies developing protein-PFAS sorption kinetics, capacity, regeneration and development of filter materials key for filter design and prototyping.		Michalsen et al. 2019

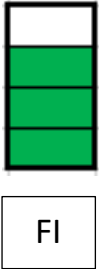
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	Cyclodextrin polymer with ionic liquid coated iron (PILI)	PFOA, PFOS, PFNA, PFBA, PFHxA, PFHxS, PFBAS, FTS 6:2	98-100% removal in the aqueous phase in groundwater.	Research and development to define kinetics of sorption and methods for regeneration of sorbents.	Regeneration testing ongoing.	Additional studies developing protein-PFAS sorption kinetics, capacity, regeneration and development of filter materials key for filter design and prototyping.		Yu 2020
12.5.4 Redox Manipulation (Transformation)	12.5.4.7 UV/Solvated electrons	PFOA=20–24 µM (8,281–9,938 µg/L) PFOS=20 µM (10,000 µg/L)	Compounds almost completely destroyed, with addition of catalysts such as sulfate and persulfate.	Certain methods do not work well under various conditions, such as acidic condition, high temperature, high reductant dosage, and high solution pH. Can be energy intensive.	No secondary waste generated.	Evaluate the impact of background interferences on degradation rates. Improve energy efficiency. Field demonstration.		Park et al. 2009; Park et al. 2011; Qu et al. 2010; Qu et al. 2014; Zhang et al. 2015; Song et al. 2013; Vellanki, Batchelor, and Abdel-Wahab 2013; Zhao, Lv, and Zhou 2012; Ochoa-Herrera et al. 2008; Bentel et al. 2019; Dong 2020; Liu 2020; Zhao 2020
	12.5.4.2 Catalyzed hydrogen peroxide (CHP)-based systems	PFOA=0.24–24 µM (99–9,938 µg/L)	Potentially effective and PFAS are transformed.	Reactions are not contaminant specific. Requires high hydrogen peroxide dosage. Less reactive PFAS species may be produced. Does not treat all PFAS. Only limited number of lab studies have been documented. May not be able to adequately distribute amendment for difficult geology. Possibility of generating PFAAs thru oxidation of precursors.	No waste generated, but incomplete reactions may produce PFAAs.	Mass balance study to better understand extent of mineralization, generation of intermediate PFAS byproducts, and PFAA end products. Impact of co-contaminants on success of PFAS treatment. Technical and cost benefits of achieving cleanup objectives. Optimize oxidant dosing and activation.		Mitchell et al. 2014; da Silva-Rackov 2016; McKenzie et al. 2016



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	12.5.4.1 Ozone-based systems (including ozone with other oxidant combinations)	PFOA and PFOS=50–20,000 µg/L PFAA precursors, PFHxS, PFHxA, PFPeA, PFBA, saturated soils=53,400 µg/kg	Potentially effective and PFAS are transformed.	High ozone and peroxide dosage. High humic acid decreases decomposition. Alkaline adjusted solutions require acidification prior to discharge. Temperature dependent. Dependent on soil permeability in soil/groundwater systems. Undesirable reaction byproducts may be generated (for example, formation of bromate when bromide ions are present).	No waste generated, but incomplete reactions may produce PFAAs.	Mass balance study to better understand extent of mineralization, generation of intermediate PFAS byproducts, and PFAA end products. Impact of co-contaminants on success of PFAS treatment. Technical and cost benefits of achieving cleanup objectives. Optimize oxidant dosing and activation.		Lin et al. 2012; Huang et al. 2016; Kerfoot 2014; Kerfoot 2016; Eberle, Ball, and Boving 2017
	12.5.4.3 Activated persulfate	PFOA=0.24–5.0 µM (99–2,070 µg/L) 6:2 FTSA=0.215 µM (97 µg/L) PFOS demonstrated at 0.1 mg/L with 79.8% reduction when coupled with electron beam	PFOA and 6:2 FTSA degraded (>90%). BTEX had no significant effect on degradation. Can be scaled up. Lower pH enhances defluorination. Energy efficient.	No transformation of PFOS unless coupled with electron beam. Need frequent injection of persulfate. Lower pH enhances scavenging of sulfate radicals at elevated temperature. Elevated temperature difficult to implement in the field at large scale. Inorganic ions hinder decomposition.	No waste generated, but incomplete reactions may produce PFAAs. Unfavorable reaction byproducts or environmental conditions may be generated.	Evaluate the impact of soil. Optimize dosing and activation.		Park et al. 2016; Liu et al. 2012; Yin et al. 2016; Lee et al. 2012a; Lee et al. 2012b; Lee et al. 2009; Kim et al. 2019
	Hydrothermal applications using reactive amendments	Sodium hydroxide, sodium borohydride, and potassium ferrate achieved >70–99% defluorination for AFFF and PFOS		High temperature and corrosive conditions required for degradation. Can form HF.	While the alkaline hydrothermal treatment process appears to be more energy-efficient than incineration, the process still requires considerable energy inputs per unit volume of contamination treated.	Improve understanding of degradation reactions and conditions. Demonstrate with different PFAS concentrates and media.		Strathmann 2020

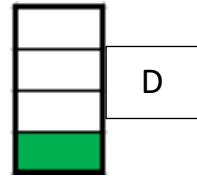
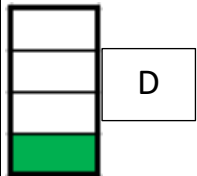
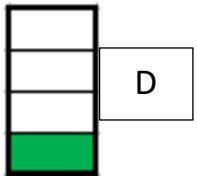
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	12.5.4.5 Photolysis/photochemical oxidation	AFFF, PFOA=0.12–217 µM (50–89,853 µg/L)	PFOA is degraded (87% up to almost 100% in dilute solution) by combined UV wavelengths between 185 and 254 nm over a 4-hour period. Current data suggest no impact on degradation rates with presence of toluene, m-xylene, and p-xylene. PFOS degraded (50% in dilute solution)	Mostly favored by acidic pH and increased catalyst concentration. Organic and inorganic constituents, such as bicarbonate, dissolved organic matter, and dissolved oxygen negatively impact decomposition. VOCs and DOC have negative impact on defluorination. Generates degradation byproducts. Incomplete defluorination at high initial concentrations.	No waste generated.	Improve energy efficiency. Conduct field demonstration.		Tang et al. 2012; Wang et al. 2008; Zhang, Pan, and Zhou 2016; Liang et al. 2016; Cheng et al. 2014; Cao et al. 2010; Giri et al. 2011; Giri et al. 2012; Hori et al. 2004; Hori et al. 2007; Chen, Zhang, and Liu 2006; Chen and Zhang 2006; Sekiguchi, Kudo, and Sankoda 2017; Gomez-Ruiz et al. 2018; Hendren 2019
		PFOS=20–37.2 µM (10,000–18,605 µg/L)	Intermediates can be further decomposed. Can be conducted at room temperature. Can be scaled up	Favored by neutral and weak alkaline conditions. Co-contaminants, such as phenol and ammonia, promote degradation. Temperature dependent. Oxygen atmosphere, low ionic strength, and presence of humic acid decrease degradation.	No waste generated.	Improve energy efficiency. Conduct field demonstration		Jin et al. 2014; Jin and Zhang 2015; Jin, Jiang, and Zhang 2017; Lyu et al. 2015a, b
	Photocatalytic treatment with BOHP/BiPO ₄	AFFF, PFCAs, GenX, PFOS treated >95% reduction in less than 20 minutes.	Energy-efficient, mineralization rates correlated to chain length.	Chloride and sulfate were shown to slow degradation rates.	No waste generated.	Improve photocatalyst composition, optimize prototypes for scale-up.		Cates 2020

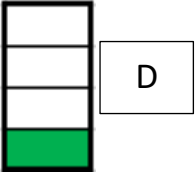
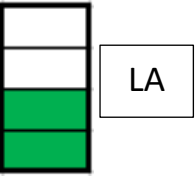
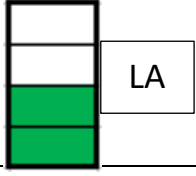
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	UV irradiation (hydrated electron) with electrochemical reduction	PFOS, PFOA, PFNA, PFSA, PFBS, PFHxS	Energy-efficient. Consumes 1/8 th energy by UV-only systems.	High reactivity of solvated electrons leads to many competing side reactions and can slow PFAS degradation.	No waste generated.	Evaluating conditions for treating different waters (i.e., degassing of oxygen), optimizing chemical additives (surfactants, sulfites, sulfate) to enhance treatment.		Jassby 2020; Rao et al. 2020; Su et al. 2019
	12.5.4.6 Electrochemical	PFCAs (C2–C8) and PFSAs AFFF GenX 6:2 FTSA=0.12–48 mM (54– 21,607 µg/L)	Degradation is not affected by dissolved organic carbon. Can be combined with other treatment technologies. PFOS and PFOA mineralization has been reported, and the transformation pathways have been proposed and documented.	May consume high energy, but more energy efficient for higher PFAS concentrations. Not all PFAS react similarly. Possibility for formation of byproducts (perchlorate, bromate), depending on the choice of electrolytes (chloride or bromide) for the electrooxidation. Electrode cost may be high and not scalable. Not all electrodes have consistent treatment results (fewer electrodes show degradation of PFOS).	No waste generated.	Assess treatment of wider range of PFAS. Limit formation of perchlorate and bromate. Build long-lasting and inexpensive electrodes. Improve energy efficiency.		Trautmann et al. 2015; Xiao et al. 2011; Lin et al. 2012; Zhou et al. 2012; Zhuo et al. 2011; Niu et al. 2012; Zhao et al. 2013; Zhuo et al. 2012; Zhuo et al. 2014; Chaplin 2014; Carter and Farrell 2008; Liao and Farrell 2009; Schaefer et al. 2015; Schaefer et al. 2017; Schaefer et al. 2019; Gomez-Ruiz et al. 2017; Trautman et al. 2015; Liang et al. 2018; Liu et al. 2019; Urtiaga et al. 2015; Soriano, Gorri and Urtiaga 2017; Pica et al. 2019; Schaefer 2020; Chaplin 2020

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	12.5.4.4 Sonochemical Oxidation/Ultrasound	PFOA=24–117 mM (9,938–48,446 µg/L) APFO=46.4 µM PFOS=20–100 µM (10,003–50,013 µg/L)	PFAS are thermally destroyed and hydroxyl radicals are generated for destruction of co-contaminants. Demonstrated in bench studies. Pilot study is demonstrated for treatment of AFFF.	Rate of reaction decreases above certain power level. Inorganics such as bicarbonate decrease reaction rate. High energy requirement. Most reported effective degradation under acidic pH and argon atmosphere with addition of catalysts such as periodate, persulfate, and sulfate. Increasing power intensity and frequency increase degradation.	No waste generated	Design and develop effective reactor with optimized operation parameters and conditions. Improve energy efficiency		Moriwaki et al. 2005; Cheng et al. 2008, 2010; Lin et al. 2015; Lin, Hu, and Lo 2016; Rodriguez-Freire et al. 2015; Lee et al. 2016; Hao et al. 2014; Vecitis et al. 2008; Cao et al. 2020
	12.5.4.8 Plasma	In groundwater: PFOA=1.4 µg/L PFOS=0.35 µg/L In prepared solutions: PFOA=1.8 µg/L PFOS=0.14 µg/L	PFOS and PFOA are degraded. Co-contaminants, such as TCE and PCE, were also treated, and did not affect treatment of PFOA and PFAS.	Recirculation of argon. High energy consumption. Limited full-scale applications for any contaminant types. Reaction byproducts are not well characterized.	No waste generated.	Further work to confirm treatment of byproducts. Cost-benefit evaluation.		Stratton et al. 2017; Jovicic et al. 2018; Singh et al. 2019; Sales 2019
	12.5.4.9 Zero-Valent Iron (ZVI), Doped ZVI, Living diatom/nano-scale ZVI	PFOS=40,000 µg/L, 372 µM (186,048 µg/L) PFOA (95.8%) and PFOS (90.7%) at 10 mg/L	Can be scaled up. Potential to combine with other technologies.	Not yet proven effective. Acidic pH required. Increased ZVI concentrations increase treatment costs. ZVI has tendency to aggregate. Diminished reactivity with aged (days old) ZVI.	PFAS concentrate on ZVI or iron oxide particles.	Further development toward increasing reactivity at higher pH. Reactivity of doped ZVI in natural water.		Arvaniti et al. 2014; Arvaniti et al. 2015; Hori et al. 2006; Albert et al. 2020
	12.5.4.10 Alkaline metal reduction (e.g., vitamin B12 w/ titanium citrate)	PFOS=30,000 µg/L	Can be scaled up. Potential to combine with other technologies (ZVI).	Requires heat increase, along with pH increase (7.5–9) for increased degradation. Primarily attacks branched polymers vs. linear.	No waste generated.	Conduct demonstration on field samples. Perform field testing. Evaluate PFOA.		Ochoa-Herrera et al. 2008

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	12.2.2 Reverse osmosis	PFOS=500–1,500,000 µg/L	Established technology. Substantial industry experience designing and operating RO membrane systems. Improvement in PFOS rejection, together with mild flux reduction (<16), was observed at longer filtration time. Flux reduction was also shown to correlate to membrane roughness, with the rougher membranes tending to experience more flux reduction than the smoother ones.	High-flux RO membranes should be avoided when treating high concentrations of PFOS, as any initial high flux exceeding the stable flux would not be sustainable and the rejection of high-flux membranes is less than that achieved using tighter membranes. High-flux membranes would perform reasonably well when treating low-strength PFOS solution, providing around 99% rejection efficiency while maintaining higher stable fluxes than tighter membranes. Multistage membrane arrays could be designed to further increase removal efficiency. A fraction of PFOS molecules might be entrapped in the polyamide layer of passage of both water and other PFOS molecules. PFOS rejection and fouling were enhanced for greater initial flux and/or applied pressure, where PFOS accumulation was promoted (probably due to increased hydrodynamic permeate drag).	Generates a high volume (~10% of flow) of concentrate (reject water) that must be managed.	Identify cost effective disposal or treatment technology for high concentration, high volume reject flow.		Tang et al. 2006; Tang et al. 2007; Thompson et al. 2011; Dickenson and Higgins 2016; Flores et al. 2013; Appleman et al. 2014

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Membrane Filtration (Separation)	12.5.3 Nanofiltration	Various per- and polyfluoroalkyl substances including PFOS, PFPnA, PFBS, PFHxA, PFHpA, PFHxS, PFOA, 6:2 FtS, PFNA, FOSA, PFDA, PFUnA, PFDS, PFDoA, PFTA, PFBA, PFPeA, PFBS; concentrations for various compounds range from lower ng/L to 10,000 µg/L	Established technology. May be functionalized to improve PFAS selectivity.	Salt passage for PFOS was reported to range from < 1% for the tighter NF-90 membrane to about 6% for the looser NF-270 and DK membranes. Flux and recovery can be limited by fouling potential of water.	Generates a concentrate that must be managed.	Full-scale spiral-wound membrane performance.		Tang et al. 2007; Steinle-Darling and Reinhard 2008; Loi-Brügger et al. 2008 (address co-contaminants); Dickenson and Higgins 2016; Wang et al. 2018; Soriano, Schaefer, and Urtiaga 2020; Liu 2020
	Ultrafiltration	PFOS: -30 to +43% removal in studies with influent concentrations of 0.0003–0.020 µg/L PFOA: 47– >98% removal in studies PFOA: negligible removal of 0.016 µg/L influent for groundwater with Cl ₂ /UF; 86% removal of 0.086 µg/L for river water using Cl ₂ /coag/floc/sand filtration/ozone/GAC/UF/RO	Low pressure filtration process (e.g., low vacuum to low pressure; 12 psi to + 40 psi). Applicable under wide range of pH (2 to 13 SU).	No sources identified UF as an effective means to remove PFAS from water. May require pretreatment to condition water to minimize UF fouling. Temperature affects water density and viscosity, which directly corresponds to flow rate across filter membranes May be effective on PFOS if combined with powdered activated carbon (PAC). "Low pressure membranes such as MF and UF are not capable of rejecting PFASs since their pore sizes are larger than the effective diameter of the PFAS molecules (~1 nm)." (Tsai et al. 2010; Rahman et al. 2014)	Typical recovery rate of UF systems is 85– >95%. Waste streams include rejectate and possibly backwash water (may be recycled but may be waste if cleaning solutions used).	Insufficient data to demonstrate efficacy.		USEPA 2019b, 2020; Atkinson et al. 2008; Flores et al. 2013; Tsai et al. 2010; Rahman et al. 2014

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12.5.5 Biodegradation (Transformation)	Fungal Enzymes	PFOA	Reduction catalyzed by extracellular ligninolytic enzymes. Process would likely be effective on organic co-contaminants.	Limited evidence of effectiveness. Growing and utilizing fungal enzymes is difficult. May be sensitive to environmental changes (e.g., temperature, pH).	No waste generated.	Understanding of mechanisms. Identification of effective strain. Development of implementation approach.		Luo 2015; Mahendra 2016
	Bacterial Enzymes	PFAAs 8:2 and 6:2 fluorotelomer alcohols, 6:2 fluorotelomer sulfonate, fluorotelomer thioether amido sulfonate, PFOA (1,000,000 µg/L)	Green solution (if demonstrated to be effective). Variety of carbon sources could be biostimulants for co-metabolism.	Limited evidence of effectiveness. Sensitive to environmental changes (e.g., temperature, pH).	No waste generated.	Understanding of mechanisms. Identification of effective bacterial strains. Evaluating FTOH transformation to a nonterminal PFAA. Development of tools to identify and assess enzymatic effectiveness.		Harding-Marjanovic et al. 2015; Wang et al. 2011; Liu and Mejia Avendaño 2013; Huang 2013; Luo 2015; Merino et al. 2016; Huang and Jaffé 2019
	Phytoremediation	PFOA, PFOS, and 26 other PFAS	Green solution if demonstrated effective.	Limited evidence of effectiveness.	Disposal of foliage and harvested materials.	Demonstrated capacity for practical use.		Zhang, Zhang, and Liang 2019

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	12.5.4.11 High-energy electron beam (eBeam)	PFOA and PFOA	Commercialized for food processing	Uncertain scale-up for PFAS and unproven for treatment of other PFAS.	Unknown.	Demonstration of applicability and suitability for PFAS.		Wang et al. 2016a; Ma et al. 2017; Pillai 2020
	12.5.7 Foam Fractionation	PFOS~0.093–0.382 mMol/L (46.5–191 mg/L); ~96% removal Lower removal rates for shorter chain compounds	May work for various PFAS compounds chains shorter than C8. Coupling separation with destructive approaches (e.g., ozofractionation) can enhance treatment.	Needs to be tested at various sites; removal depends on foam depth, ionic strength of solution, and aeration rates.	Generates waste stream that still needs disposal	Understanding the mechanism of removal for the various chain lengths.		Meng et al. 2018; Dai et al. 2019; Lyu et al. 2020; Buckley et al. 2021; Burns, Stevenson and Murphy 2021
	12.5.8 Deep Well Injection	Could be used for all substances.	Could be a secure disposal method if proper geological formation is identified.	Cost, regulatory approval, and community acceptance.	No residual waste expected.	Demonstration of operational considerations to ensure proper transport and disposal of PFAS.		USEPA 2019a

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