


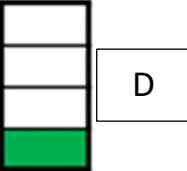


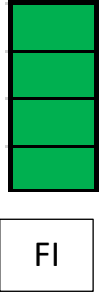

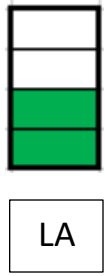
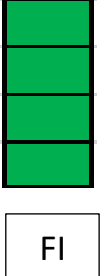
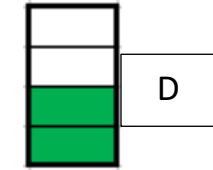





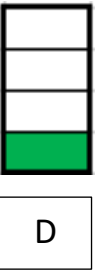
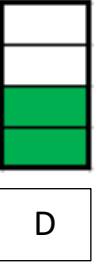

Table 12-1. LIQUID TECHNOLOGIES—REMEDATION TECHNOLOGIES AND METHODS COMPARISON								
<p>FI—FIELD IMPLEMENTED LA—LIMITED APPLICATION D—DEVELOPING</p> <p>This table belongs with the ITRC PFAS Tech Reg Document. The ITRC intends to update this table periodically as new information is gathered. The user is encouraged to visit the ITRC PFAS web page (http://pfas-1.itrcweb.org) to access the current version of this file. Please see ITRC Disclaimer http://pfas-1.itrcweb.org/about-itrc/#disclaimer.</p> <p>The mechanism of treatment (separation vs. transformation) is listed under each Remediation Technology Group.</p>								
Remediation Technology Group	Remediation Technology Document Sections included	What PFAS Demonstrated On? What Concentrations/Removal Reported?	Strengths (Includes Co-Contaminants, Sustainability, Scalability)	Challenges/Limitations (Includes Co-Contaminants, Sustainability, Scalability)	Waste Management/Life Cycle	Future Data Needs	PFAS Demonstration Maturity (Lab, Field Pilot, Full-Scale, Commercialized)	References
12.4.2 Flocculation/Coagulation (Separation)	12.4.2 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)

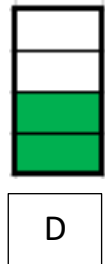
Ferric salts	PFOA/PFOS~1,000 µg/L, 1–50% removal based on coagulant dosage; removal improved to 48–95% at pH 4; PFOA~8 µg/L, 15% removal PFOS~236 µg/L, 30% removal	Conventional technology. Used commonly for water treatment in other applications. Readily scalable.	Current data show that ferric salts are 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)
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		(Yang et al. 2016; Lin, Wang, et al. 2015; Wang, Lin, et al. 2016)



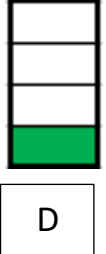
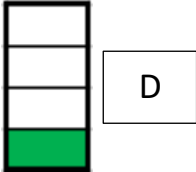
						initial concentrations (ng/L level).		
Sorption (Separation)	12.2.1.1 Granular activated carbon (GAC)	Demonstrated for all PFAS tested to date at parts per trillion to parts per billion concentrations for aboveground activated carbon treatment	Treats all tested PFAS to date with high removals prior to 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). Pretreatment may be necessary.	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)
	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)



<p>12.4.1.1 Colloidal activated carbon (in situ treatment)</p>	<p>Demonstrated full-scale on broad range of PFAS contaminants</p>	<p>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.</p>	<p>PFAS contaminants are immobilized, not destroyed. Certain co-contaminants may reduce efficacy.</p>	<p>No waste generated.</p>	<p>Limited number of full-scale applications to date. Need documentation of longevity.</p>		<p>(McGregor 2018; Carey et al. 2019)</p>
<p>12.2.1.2 Anionic exchange resins (AEX or IX)</p>	<p><i>Demonstrated for all PFAS tested to date at parts per trillion to parts per billion concentrations for aboveground anionic exchange resins.</i> Shorter chain PFAS breakthrough faster. Low or high concentration for single use nonregenerable resin; high concentration for regenerable resin.</p>	<p>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.</p>	<p>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. <i>No destruction of PFAS, unless it is incinerated at high temperature (>1,100°C).</i></p>	<p>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.</p>	<p>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.</p>		<p>(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)</p>

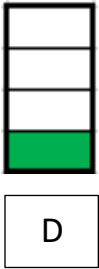
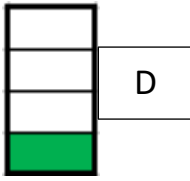
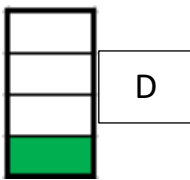
	12.4.1.4 Biochar	Treatment appears to be demonstrated for all PFAS tested to date. Most effective for longer chain PFAS.	Possible alternative to GAC. Effectiveness increases with surface area.	Only proven effective on ultrapure water. Natural organic matter reduces effectiveness. Slow reaction kinetics.	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)
	12.4.1.3 Zeolites/clay minerals (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 clay 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)
	12.4.1.2 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)
12.4.4 Redox Manipulation (Transformation)	12.4.4.7 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)

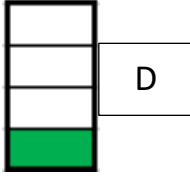
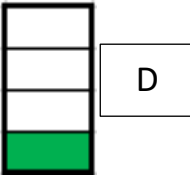
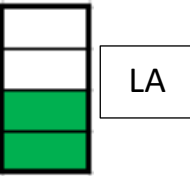
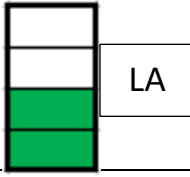
	12.4.4.2 Catalyzed hydrogen peroxide-based systems	PFOA=0.24–24 µM (99–9,938 µg/L)	Potentially effective and PFAS are transformed.	Reactions are not contaminant specific. Requires high hydrogen peroxide dosage. Less reactive PFAS species may be produced. Does not treat all PFAS. Only limited number of 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)
	12.4.4.1 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)
	12.4.4.3 Activated persulfate	PFOA=0.24–5.0 µM (99–2,070 µg/L) 6:2 FTSA=0.215 µM (97 µg/L)	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. 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, Lo, Kuo, and Lin 2012; Lee, Lo, Kuo, and Hsieh 2012; Lee et al. 2009)

	12.4.4.5 Photolysis/photochemical oxidation	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.	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.	D	(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 2006; Chen and Zhang 2006; Sekiguchi, Kudo, and Sankoda 2017)
		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)
	12.4.4.6 Electrochemical	PFCAs (C2–C8) and PFSAs 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; Carter and Farrell 2008; Liao and Farrell 2009; Schaefer et al. 2015; Schaefer et al. 2017; Gomez-Ruiz et al. 2017; Urtiaga et al. 2015)

<p>12.4.4.4 Sonochemical Oxidation/Ultrasound</p>	<p>PFOA=24–117 mM (9,938–48,446 µg/L) APFO=46.4 µM PFOS=20–100 µM (10,003–50,013 µg/L)</p>	<p>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.</p>	<p>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.</p>	<p>No waste generated</p>	<p>Design and develop effective reactor with optimized operation parameters and conditions. Improve energy efficiency</p>		<p>(Moriwaki et al. 2005; Cheng et al. 2008, 2010; Lin, Lo, 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)</p>
<p>12.4.4.8 Plasma</p>	<p>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</p>	<p>PFOS and PFOa are degraded. Co-contaminants, such as TCE and PCE, were also treated, and did not affect treatment of PFOA and PFAS.</p>	<p>Recirculation of argon. High energy consumption. Limited full-scale applications for any contaminant types. Reaction byproducts are not well characterized.</p>	<p>No waste generated.</p>	<p>Further work to confirm treatment of byproducts. Cost-benefit evaluation.</p>		<p>(Stratton et al. 2017; Jovicic et al. 2018)</p>
<p>12.4.4.9 Zero-Valent Iron (ZVI), Doped ZVI</p>	<p>PFOS=40,000 µg/L, 372 µM (186,048 µg/L)</p>	<p>Can be scaled up. Potential to combine with other technologies.</p>	<p>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.</p>	<p>PFAS concentrate on ZVI or iron oxide particles.</p>	<p>Further development toward increasing reactivity at higher pH. Reactivity of doped ZVI in natural water.</p>		<p>(Arvaniti et al. 2014; Arvaniti et al. 2015; Hori et al. 2006)</p>
<p>12.4.4.10 Alkaline metal reduction (e.g., vitamin B12 w/ titanium citrate)</p>	<p>PFOS=30,000 µg/L</p>	<p>Can be scaled up. Potential to combine with other technologies (ZVI).</p>	<p>Requires heat increase, along with pH increase (7.5–9) for increased degradation. Primarily attacks branched polymers vs. linear.</p>	<p>No waste generated.</p>	<p>Conduct demonstration on field samples. Perform field testing. Evaluate PFOA.</p>		<p>(Ochoa-Herrera et al. 2008)</p>

Membrane Filtration (Separation)	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.	 FI	(Tang et al. 2006; Tang et al. 2007; Thompson et al. 2011; Dickenson and Higgins 2016; Flores et al. 2013; Appleman et al. 2014)
	12.4.3 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	Not studied, but possible depending on molecular size and anionic charge.	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.	 D	(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)

		ng/L to 10,000 µg/L						
	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 Cl2/UF; 86% removal of 0.086 µg/L for river water using Cl2/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 Drinking Water Treatability Database Introduction (USEPA 2019b); USEPA Drinking Water Treatability Database (USEPA 2020); (Atkinson et al. 2008; Flores et al. 2013; Tsai et al. 2010; Rahman et al. 2014)
12.4.5 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)
	Bacterial Enzymes	8:2 and 6:2 fluorotelomer alcohols, 6:2 fluorotelomer sulfonate, fluorotelomer thioether amido	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. Development of tools to identify and assess enzymatic effectiveness.		(Harding-Marjanovic et al. 2015; Wang et al. 2011; Liu and Mejia Avendaño 2013; Luo 2015; Huang and Jaffé 2019)

		sulfonate, PFOA (1,000,000 µg/L)						
	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)
	12.4.6 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, Batchelor, et al. 2016; Ma et al. 2017)
	12.4.7 Surface Activation 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.	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)
	12.4.8 Deep Well Injection	Could be utilized 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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