Treatment technologies for PFAS in environmental waters and soils

Treatment technologies aimed at rendering water suitable for human consumption were addressed separately and earlier in this report, reflecting their prioritization by the Government of Jersey. In this section, the focus shifts to treatment technologies applicable to other water types; namely wastewater, surface water, and groundwater, which are collectively referred to as "environmental waters," as well as to soils contaminated with PFAS. These technologies leverage the physical and chemical properties of contaminants to immobilize, separate, or destroy them. However, the distinctive characteristics of PFAS, particularly their extreme persistence and high mobility in both soils and water, render many conventional treatment methods ineffective. A range of specialized technologies is available, which may be deployed either ex situ (e.g., by extracting and treating contaminated groundwater) or in situ (e.g., by injecting sorptive materials directly into subsurface soils). Selecting an appropriate treatment approach requires a comprehensive understanding of site-specific contamination, a review of proven technological options, and the use of monitoring tools to track progress and ensure regulatory compliance.

At a PFAS-contaminated site, a so-called conceptual site model (CSM) is essential for justifying the chosen treatment approach. A PFAS-focused CSM integrates multiple layers of site-specific information to understand and manage contamination. A CSM typically covers:

- Sources of PFAS: Identifies where PFAS originated (e.g., firefighting foam, industrial discharge).
- Contaminant types: Details which PFAS compounds are present, including precursors and breakdown products.
- Transport mechanisms: Explains how PFAS moves through soil, groundwater, and surface water.
- Exposure pathways: Maps how humans or ecosystems might come into contact with PFAS (e.g., drinking water, food chain).
- Geological and hydrological context: Describes subsurface conditions that affect PFAS mobility, such as aquifer properties, pH, and redox conditions.
- Receptor locations: Highlights sensitive areas such as residential zones, water wells, or ecological habitats.

Many treatment technologies have limited capacity and uncertain effectiveness. The selection of a treatment technology for PFAS is influenced by several factors:

- PFAS Properties: PFAS are defined by strong carbon-fluorine bonds, which contribute to their chemical stability and resistance to degradation. Their behavior is influenced by ionic states (anionic, cationic, or zwitterionic), functional groups (e.g., carboxylates and sulfonates), perfluoroalkyl chain length and branching, acidity, etc. These characteristics directly affect how PFAS interact with environmental media and respond to treatment technologies.
- Environmental Conditions: PFAS behavior in the environment is influenced by a range of factors, including natural processes and interactions with co-contaminants such as petroleum hydrocarbons, organic matter, and minerals. These interactions can increase PFAS mobility, alter partitioning behavior, and facilitate the transformation of precursor compounds into more stable and persistent perfluoroalkyl acids (PFAAs). Environmental conditions, particularly redox potential, pH, total organic carbon, and competing anions, play a critical role in determining PFAS distribution, degradation pathways, and the overall

effectiveness of treatment technologies. Understanding these site-specific variables is essential for designing and implementing successful remediation strategies.

- Community Input: Stakeholder engagement is critical in remedy selection. Community members often weigh trade-offs between cost, level of cleanup, long-term effectiveness, and the acceptability of residual contamination. Transparent communication and inclusive decision-making help build trust and support for remediation strategies.
- Technology Suitability: The effectiveness of PFAS treatment technologies depends heavily on site-specific conditions and the nature of the waste stream. For example, sorption methods such as granular activated carbon (GAC) and ion exchange (IX) media are well-suited for treating large volumes of water with low PFAS concentrations (as well as low organic matter content and co-contaminants). In contrast, destructive technologies are more appropriate for small volumes of high-concentration liquids.

Below we divide the treatment technologies broadly into those for 1) treating PFAS in environmental waters (primarily contaminated wastewaters, surface waters and groundwater) and 2) those for treating PFAS in soils. We have ordered the treatment technologies, starting with those treatment technologies with the highest technology readiness levels (TRLs) and then finishing the sections with the emerging treatment technologies which are some years from implementation. The TRL Scale (Levels 1–9) is described in Table 1.

Table 1. Summary of technology readiness levels (TRLs)

TRL	Description	Stage
1	Basic principles observed	Early research
2	Concept formulated	Hypothesis stage
3	Experimental proof of concept	Lab validation
4	Technology validated in lab	Bench-scale testing
5	Technology validated in relevant environment	Simulated field conditions
6	Prototype demonstrated in relevant environment	Pilot-scale testing
7	System prototype in operational environment	Field demonstration
8	System completed and qualified	Full-scale implementation
9	Proven in operational use	Commercial deployment

For example, granular activated carbon (GAC) for PFAS removal from water is typically TRL 9, while electrochemical oxidation, described by one of the subject matter experts, is TRL 5–7 depending on the specific application.

Treatment technologies for PFAS in environmental waters

Sorption technologies

Sorption technologies are used both ex situ and in situ to treat PFAS-contaminated environmental waters. Ex situ setups may employ multiple sorption media types in series to enhance removal efficiency. The two main types of sorption technologies used for drinking water treatment (GAC and IX) can also be used for treatment of PFAS in environmental waters. However, most full-scale GAC and IX systems focus on treating PFOA and PFOS in drinking water, with limited data on other PFAS or different water sources.(Tshangana, Nhlengethwa et al. 2025) Treating groundwater from areas such as fire training zones often requires more complex pretreatment (e.g. surface active foam fractionation (SAFF)) and frequent media replacement due to higher contaminant levels, leading to increased operational costs. As is the case for drinking water treatment, designing an effective sorption treatment system for PFAS-contaminated environmental waters involves lab and pilot testing to determine parameters like bed depth, contact time, media consumption rate, and breakthrough projections. Tests should use site-specific water to account for local geochemistry. As previously discussed, membrane filtration technologies such as nanofiltration and reverse osmosis are highly effective for removing PFAS from drinking water. However, they are less effective for environmental waters impacted by PFAS, such as surface or groundwater, which often contain organic matter and other contaminants that foul membranes and reduce performance.(Tshangana, Nhlengethwa et al. 2025) Managing the concentrated waste stream also becomes more complex, making these systems less practical for large-scale environmental remediation.

Injectable colloidal activated carbon (CAC) is a passive in situ treatment designed to immobilize PFAS in contaminated groundwater and prevent its migration toward sensitive receptors such as drinking water wells or surface water bodies.(Carey, Hakimabadi et al. 2022) The fine carbon particles are injected directly into aquifer flux zones, where they bind PFAS quickly and effectively, outperforming traditional GAC in sorption kinetics. CAC has been successfully applied at multiple sites globally, showing long-term effectiveness, often reducing PFAS to non-detect levels for years.(McGregor 2018, Carey, Hakimabadi et al. 2022) Its performance depends on site-specific factors such as PFAS type, contaminant flux, and aquifer conditions. Compared to pump-and-treat systems (i.e., groundwater pumped up and treated ex-situ), CAC offers a more sustainable solution with minimal energy use and a significantly lower carbon footprint, making it well-suited for treating PFAS in natural groundwater systems.(McGregor 2018, Carey, Hakimabadi et al. 2022)

Several emerging sorption technologies show promise for treating PFAS-contaminated environmental waters, particularly groundwater. Polymer-coated sand, using cyclodextrin-based polymers, offers high selectivity and mechanical stability, with strong performance for PFOA and PFOS and excellent regenerability.(Badruddoza, Bhattarai et al. 2017) Surface-modified clays and zeolites use ion exchange and hydrophobic interactions to remove PFAS, including short- and long-chain variants, and have demonstrated resistance to fouling in complex groundwater matrices.(Han, Rafiq et al. 2019) Biochar, derived from biomass, is a low-cost, carbon-rich material with good affinity for organic contaminants, though its performance and consistency vary across batches.(Inyang and Dickenson 2017) Hydrogels and fluorogels are especially effective for short-chain PFAS due to their high selectivity and rapid sorption kinetics, and some formulations can be regenerated for reuse.(Kumarasamy, Manning et al. 2020) While most of these technologies are still in early stages or pilot testing, they offer promising alternatives to conventional media for in situ or ex situ treatment of PFAS in environmental waters.

Interface-driven separation technologies for PFAS in environmental waters

Beyond sorption, a growing class of PFAS treatment technologies focuses on separating and concentrating contaminants from environmental waters, such as groundwater, landfill leachate, and wastewater, before destruction. These interface-driven separation technologies rely on physical or chemical boundaries to isolate PFAS efficiently, especially in complex water matrices where conventional adsorptive methods like GAC, ion exchange, and membranes may struggle.

SAFF is one of the most promising approaches for PFAS-impacted environmental waters.(We, Zamyadi et al. 2024) It uses air bubbles to lift PFAS to the surface and concentrate them in foam. Unlike GAC, IX, and membrane technologies, SAFF performs well in the presence of organic matter and co-contaminants and thus requires minimal pre-treatment. However, concerns remain about airborne PFAS emissions during operation and the need for safe foamate disposal or destruction. Despite these challenges, SAFF has demonstrated strong performance in field applications and is gaining traction as a scalable solution.

Precipitation, coagulation, and flocculation are conventional separation methods that use chemical or electrochemical coagulants to form solids that capture PFAS through co-precipitation.(Lin, Wang et al. 2015) These methods have shown success in bench-scale studies (particularly electrocoagulation(Lin, Wang et al. 2015)) but face challenges in full-scale deployment due to variability in performance and the need for careful quality control. They are best suited as pre-treatment steps to reduce PFAS mass before applying more advanced destruction technologies. The solid waste generated requires proper disposal, and specialty coagulants for PFAS applications are still under evaluation.

Water aggregation and separation (WAS) is an emerging technology developed at the Colorado School of Mines that isolates PFAS at the gas–water interface, similar in principle to SAFF (personal communication from Professor Chris Higgins at Colorado School of Mines, US). WAS is designed to concentrate PFAS from dilute water streams, reducing the volume of contaminated waste and making downstream destruction more efficient. Though still under development, WAS offers a low-energy, scalable pathway for PFAS separation and is being explored as part of integrated treatment trains. Its reliance on interfacial behaviour makes it particularly well-suited for environmental waters with complex chemistries. While WAS itself is not yet formally published, its principles align with recent findings from Schrama et al. (2024) (Schrama, Massimi et al. 2024) on PFAS behaviour at interfaces and light-driven degradation.

Destruction technologies for PFAS in environmental waters

Although many PFAS destruction technologies were originally developed for treating concentrated waste streams and complex environmental waters, several are now being explored for application in drinking water treatment. This reflects growing regulatory pressure to achieve complete PFAS removal and minimize residual waste. However, compared to mature sorption technologies such as GAC and IX, which operate at TRL 8–9 and are widely deployed in drinking water systems, most destruction technologies remain at lower TRLs (typically TRL 3–7). Their use in potable water treatment is therefore limited to lab-scale pilot studies. The following section reviews these emerging destruction technologies, highlighting their mechanisms, performance, and potential roles in future integrated treatment trains.

Redox manipulation involves chemical oxidation or reduction to break PFAS molecular bonds with some promising bench-scale and limited field results.(Nzeribe, Crimi et al. 2019). However, complete defluorination is rarely achieved and transformation products may persist. Ozone-based systems use ozone combined with other oxidants like hydrogen peroxide or persulfate to generate reactive radicals that can degrade PFAS.(Thomas, Jenkins et al. 2020) Bench and limited field-scale studies show promising PFAS reductions, but the exact degradation mechanisms remain unclear. Sorption may also contribute to observed reductions. While effective as a polishing step, more research is needed to confirm full PFAS destruction and by-product formation. Catalyzed hydrogen peroxide (CHP)-based systems rely on hydrogen peroxide and metal catalysts to produce hydroxyl radicals that partially transform PFAS precursors into stable PFCAs.(Bruton and Sedlak 2017) Some systems also generate superoxide and hydroperoxide, which have shown potential to mineralize PFOA in bench tests. However, field-scale effectiveness is limited, and transformation often stops at intermediate compounds, making CHP more suitable for partial degradation or precursor treatment.

Activated persulfate uses chemical activation (via heat, pH, or metals) to generate sulfate and hydroxyl radicals that degrade PFAS.(Bruton and Sedlak 2017) Under acidic conditions, sulfate radicals can fully mineralize PFCAs like PFOA through decarboxylation and HF elimination, but PFOS and other PFSAs remain largely unreactive. At high pH, hydroxyl radicals transform PFAS precursors into stable PFCAs. While effective for certain PFAS, especially under acidic conditions, its broader applicability is limited by incomplete degradation and variable reactivity.

Sonochemical oxidation uses high-frequency ultrasound to create cavitation bubbles that generate extreme heat, pressure, and free radicals, leading to rapid PFAS breakdown.(Gole, Sierra-Alvarez et al. 2018) Bench and field-scale studies show >90% defluorination of PFOA and PFOS, with mineralization to fluoride, sulfate, and carbon dioxide. It's considered one of the most effective PFAS destruction methods, especially for groundwater, and can be enhanced by combining with persulfate for synergistic effects.(Lei, Tian et al. 2020)

Photolysis/photochemical oxidation uses UV or vacuum UV light, often combined with catalysts like TiO_2 or persulfate, to generate reactive radicals that break PFAS bonds.(Wang, Yang et al. 2017) While direct photolysis is limited due to PFAS' low light absorption, photochemical oxidation can degrade PFAS through radical-driven reactions. It's most effective under controlled conditions and can mineralize PFAS into shorter chains, fluoride, and carbon dioxide. Emerging methods like porous media photocatalysts and boron nitride may enhance performance, but field-scale validation is still limited.

Electrochemical treatment uses anodic oxidation to degrade PFAS directly at the electrode or indirectly via radicals formed in solution.(Smith, Lauria et al. 2023) Boron-doped diamond electrodes are most commonly used due to their durability and effectiveness.(Smith, Lauria et al. 2023) Bench and pilot studies show strong PFAS removal, including short- and long-chain compounds and precursors, with fluoride release as a byproduct.(Smith, Lauria et al. 2023) It's suitable for treating concentrated PFAS waste and is being explored for in situ use. Managing byproducts like perchlorate and optimizing operating conditions are key to successful application.

Solvated electron-based advanced reduction processes use activation techniques such as ultraviolet light, ultrasound, or chemical reductants to generate hydrated electrons, highly reactive species capable of cleaving the strong carbon-fluorine bonds.(Cui, Gao et al. 2020) They are effective for PFOS and PFOA under controlled laboratory conditions. However, the presence of oxygen and other radical scavengers can significantly reduce treatment efficiency. Despite these challenges, recent studies have reported high defluorination rates in short time periods, highlighting the potential of this technology for high-performance PFAS degradation.

Plasma technology employs electrical discharges to create reactive species that rapidly degrade PFAS in water.(Stratton, Dai et al. 2017) Nonthermal plasma is preferred for water treatment due to lower energy demands. It can achieve up to 90% PFAS degradation in short timeframes and is unaffected by co-contaminants. Plasma technology is also considered environmentally friendly and suitable for a diversity of environmental waters.

Zero-valent iron (ZVI)/doped-ZVI is an in situ reductive technology that removes PFAS through surface-mediated reactions.(Arvaniti, Hwang et al. 2015) Nanoscale ZVI offers enhanced reactivity and injectability. It has been proven effective for PFOS degradation, with fluoride release confirming breakdown. Surface coatings such as Mg-aminoclay can improve performance.

Alkaline metal reduction uses alkali metals and catalysts such as vitamin B12 to chemically reduce PFAS, particularly branched PFOS isomers.(Zenobio, Modiri-Gharehveran et al. 2020) Bimetallic nNiFe0 particles supported on activated carbon have demonstrated transformation of both linear- and branched-PFOS isomers, achieving 94% PFOS transformation at 50°C. (Zenobio, Modiri-Gharehveran et al. 2020) Transformation byproducts detected in the particle extracts indicate defluorination and desulfonation pathways.

High-energy electron beam (eBeam) applies ionizing radiation to generate reactive species that degrade PFAS in water and soil without added chemicals. (Wang, Batchelor et al. 2016) Bench studies show up to 95% defluorination of PFOA and PFOS, with effectiveness influenced by water chemistry and dose.(Wang, Batchelor et al. 2016) It's a promising ex situ technology for concentrated PFAS waste streams.

Supercritical water oxidation (SCWO) uses high temperature and pressure to destroy PFAS and co-contaminants in complex aqueous waste.(McDonough, Kirby et al. 2022, Scheitlin, Dasu et al. 2023) Effective for both carboxylic and sulfonic PFAS at ≥450°C and ≥575°C, respectively.(Scheitlin, Dasu et al. 2023) SCWO is well-suited for industrial-scale applications and has shown consistent performance across varied waste matrices.

Microbial and fungal degradation of PFAS is possible for some polyfluorinated compounds and precursors, but PFOA and PFOS remain highly resistant.(Liu and Avendano 2013, Idris and Erasmus 2024) Recent studies show partial defluorination using specific bacteria and enzymes, though transformation often leads to persistent byproducts. Research is ongoing to identify effective strains and conditions for broader PFAS biodegradation.

Alkaline hydrothermal reaction, also known as HALT (Hydrothermal Alkaline Treatment), is a high-temperature, high-pressure, and high-pH process designed to chemically destroy PFAS, particularly stubborn compounds like PFOS.(Wu, Hao et al. 2019) The method breaks PFAS down into harmless end products such as fluoride and carbonate salts. It has shown impressive results, achieving over 90% degradation in various water types, and even exceeding 99% in continuous flow systems. Although it typically requires longer treatment times,(Pinkard, Austin et al. 2023) HALT is emerging as a powerful option for concentrated PFAS waste and is being explored for broader use in environmental water remediation.

Treatment technologies for PFAS in soils

PFAS-contaminated soils present unique challenges due to their complex composition and the persistent nature of these compounds. PFAS-contaminated soils can be treated using a limited number of technologies, primarily applied ex situ. These include excavation and disposal, soil washing, sorption/stabilization, phytoremediation, thermal treatment and electrokinetic remediation.

Excavation and disposal

Excavation and disposal is a proven method for managing a wide range of contaminated soils including PFAS-contaminated soils, involving the removal of impacted material and its transport to a permitted landfill, followed by backfilling with clean soil. While this approach effectively eliminates the source of contamination, it does not destroy PFAS and may contribute to PFAS in landfill leachate. Stabilizing agents can be added prior to disposal to reduce leachability, and in some cases, soils may be treated on site using sorption or thermal methods before reuse or disposal.

This method is widely implemented but faces challenges due to evolving regulations and limited landfill acceptance of PFAS waste. Disposal in unlined or improperly lined landfills should be avoided to prevent environmental release. Sustainability concerns include emissions from excavation and transport, resource use for backfill, and community impacts such as traffic and noise.(Söderqvist, Brinkhoff et al. 2015) Despite its high cost, excavation and disposal can be a permanent and viable solution for smaller volumes of contaminated soil.

Soil washing

Soil washing is a field-implemented, ex situ treatment technology that removes PFAS from soil through physical separation and chemical extraction. It targets the finer soil fractions, such as clays and silts, where PFAS tend to accumulate due to higher organic carbon content and stronger hydrophobic interactions.(Quinnan, Morrell et al. 2022) The process uses water or surfactant-based wash solutions to separate fine and coarse particles, transferring PFAS from the solid phase into the liquid phase for follow-up treatment or disposal.

Mechanical separation tools like vibratory screens, trommels, and hydrocyclones help isolate the PFAS-rich fine fraction, which is then managed separately. Coarser fractions, such as sands and gravels, often meet cleanup goals and can be reused or returned to the site. Field demonstrations have shown PFOS removal efficiencies of 94–99% in coarse fractions and up to 89% in finer soils, with total soil volume reductions exceeding 90%.(Quinnan, Morrell et al. 2022)

Design considerations include soil grain size distribution, moisture content, and PFAS concentration variability. Soils with high clay content or inconsistent feed conditions may require preprocessing. Optimal particle sizes range from 0.25–2 mm, while soils with more than 50% fines may be less viable for treatment. Wash solution treatment, retention time, and throughput must be carefully managed to ensure efficiency.

Although energy-intensive, soil washing can reduce the need for off-site disposal and allow reuse of treated soils if regulatory criteria are met. The wash solution can be recycled, but the fine fraction that fails cleanup standards must be disposed of properly. Soil washing offers a scalable and effective option for reducing PFAS mass in contaminated soils, especially when particle size separation is feasible.

Sorption and stabilization/solidification

Sorption and stabilization/solidification are field-implemented techniques used to immobilize PFAS in contaminated soils and reduce leaching to groundwater and surface water.(Sörengård, Östblom et al. 2020) These methods involve mixing PFAS-binding amendments, such as powdered activated carbon, carbon-mineral blends, surface-modified clays, or cementitious binders, into the soil either in situ or ex situ.(Sörengård, Östblom et al. 2020) In situ mixing is performed with standard construction equipment, while ex situ treatment may use pug mills or similar systems. When applied correctly, these amendments form a low-permeability matrix that restricts PFAS mobility and minimizes environmental transport.(Sörengård, Östblom et al. 2020)

While effective at immobilization, these technologies do not destroy PFAS and may limit future treatment options, particularly in situ. Stabilized soils may be difficult to re-treat and could require excavation for further remediation. Additionally, erosion in flood-prone areas poses a risk of off-site transport. Environmental factors such as soil pH, organic content, ionic strength, and co-contaminants influence sorption performance. High organic content can reduce effectiveness, while low pH and the presence of polyvalent cations may improve PFAS binding. Long-term stability has been demonstrated through simulated aging tests, and reductions in PFAS uptake by plants and earthworms have also been observed.

To ensure success, site-specific treatability testing is essential to determine the appropriate amendment type, dose, and delivery method and post-treatment testing is also needed. These technologies offer a practical, scalable solution for managing PFAS in soil source zones, especially when long-term containment is the primary objective.

Phytoremediation

Phytoremediation has emerged as a promising, low-cost strategy for managing PFAS-contaminated soils, particularly in settings where conventional remediation methods are impractical or prohibitively expensive.(Mayakaduwage, Ekanayake et al. 2022, Naveed, Oladoye et al. 2024) Its appeal lies not only in its energy efficiency and environmental friendliness but also in its potential for community engagement and aesthetic integration into landscapes. While phytoremediation has demonstrated moderate success with other contaminant classes, its application to PFAS is still in early stages, with growing interest from researchers, regulators alike.

The primary mechanism of interest for PFAS is phytoextraction, wherein plants take up PFAS via the roots and transfer them the above-ground plant parts (shoots and leaves), which can then be harvested and removed from the site. Other phytoremediation pathways (i.e., phytostabilization, rhizodegradation, and phytovolatilization are less relevant for PFAS due to their chemical stability and resistance to degradation). A wide range of plant species have shown the ability to accumulate PFAS, though uptake varies significantly depending on both the plant and the specific PFAS. (Mayakaduwage, Ekanayake et al. 2022, Naveed, Oladoye et al. 2024)

Bioaccumulation factors (BAFs) are a key determinant of phytoremediation effectiveness and vary between the specific plant species and PFAS. Shorter-chain PFAS with 3-4 perfluoroalkyl carbons have BAFs around 10, indicating relatively high uptake potential, whereas longer-chain PFAS (e.g., PFOA and PFOS, with 7-8 perfluoroalkyl carbons) typically show BAFs closer to 1, reflecting limited translocation into plant tissues.(Lesmeister, Lange et al. 2021) These differences underscore the importance of selecting appropriate plant species and targeting specific PFAS profiles. Moreover, soil characteristics, including pH, organic matter content, and moisture, play a critical role in PFAS mobility and plant uptake. (Mayakaduwage, Ekanayake et al. 2022, Naveed, Oladoye et al. 2024)

A recent field-scale trial at the former Loring Air Force Base in Maine demonstrated the potential of fiber hemp (Cannabis sativa) for PFAS phytoextraction.(Nason, Thomas et al. 2024) The study found that hemp absorbed 10 PFAS compounds, with higher accumulation in leaves than stems and greater uptake of short-chain PFCAs than PFSAs. The ChinMa hemp variety showed the most robust growth and removal efficiency, extracting approximately 1.4 mg of PFAS from soil and achieving up to 2% removal in the most successful plot. This removal achieved in one growing season was only in the localized root zone and not the entire contaminated area and most PFAS removed were the shorter-chain PFAS. Post-harvest hydrothermal liquefaction (HTL) of hemp biomass degraded nearly all carboxylic acids and reduced extractable organic fluorine, offering a viable pathway for PFAS destruction.(Nason, Thomas et al. 2024)

Despite its advantages, phytoremediation of PFAS is constrained by slow remediation rates of longer-chain PFAS. At typical biomass harvest rates of 5 metric tons dry weight per hectare per year, estimated timeframes for meaningful PFAS removal range from 50 to 500 years.(Cornelissen, Briels et al. 2025) However, the identification and deployment of hyperaccumulator crops with elevated BAFs could reduce remediation times, for shorter-chain PFAS at least.

Thermal treatment

The only destruction technologies available for PFAS in soils, sediments and solid wastes are various thermal treatments which encompass a range of high-temperature processes.(Longendyke, Katel et al. 2022) These include incineration, pyrolysis, and gasification, each varying in temperature, mechanism, and maturity. Ex situ thermal destruction (e.g., incineration) has been tested at temperatures up to 1100°C and shown to be effective, achieving PFOS removal rates above 99%.(Longendyke, Katel et al. 2022) While in situ thermal treatment has not yet been field-demonstrated, bench-scale results suggest it may be feasible.(Kang, Birch et al. 2023)

Incineration, a subset of thermal treatment, uses combustion with heat and oxygen to mineralize PFAS in solids and liquids. It is a mature technology applied to various hazardous wastes, though its effectiveness for PFAS is still under investigation. Recent studies have documented destruction efficiencies exceeding 99% for certain PFAS, (Longendyke, Katel et al. 2022) but the specific conditions required for complete breakdown remain unclear (e.g. is the 850°C for 2 seconds typically used in municipal solid waste incineration sufficient?).

All thermal processes face similar challenges: achieving uniform heating, managing air emissions, and controlling hazardous by-products such as hydrogen fluoride. Off-gas treatment systems such as scrubbers are essential for safe operation. Pyrolysis and gasification, typically used for energy recovery, are now being evaluated for PFAS destruction but remain in early development.

Thermal treatment is energy-intensive and costly, with sustainability concerns tied to fuel use, transportation, and air emissions. Nonetheless, it offers one of the few pathways for permanent PFAS destruction and may be viable for smaller volumes of highly contaminated soil, sediments and biosolids, especially when other technologies fall short. Ongoing research is focused on optimizing process parameters and understanding environmental risks to support broader implementation.

Electrokinetic remediation

Electrokinetic remediation (EKR) is an emerging in-situ technology that applies a low-voltage electric field across contaminated soils to mobilize ionic PFAS compounds toward electrodes for capture or degradation.(Niarchos, Sörengård et al. 2022) It is particularly promising for shorter-chain PFAS, but removal of longer-chain PFAS is a more challenging. Combining EKR with other techniques (e.g., stabilisation) could potentially increase removal efficiency of longer-chain PFAS. While still at a low TRL for PFAS, bench-scale studies have demonstrated measurable removal and defluorination under optimized conditions. Challenges remain in scaling the technology and managing energy inputs, but EKR offers a potentially viable pathway for in-situ treatment of PFAS in source zone soils.

Conclusions

The PFAS treatment technologies reviewed here span a wide range of TRLs, reflecting their maturity, field validation, and suitability for different environmental media (Tables 2 and 3). In both environmental waters and contaminated soils, treatment selection depends on site-specific factors such as PFAS type, concentration, co-contaminants, and regulatory goals. This review may not have been exhaustive as developing new treatment technologies for PFAS is a vibrant area of research that attracts a lot of funding.

In environmental waters, including groundwater, surface water, and landfill leachate, several high-TRL technologies are widely deployed. GAC and IX are mature (TRL 8–9), field-proven methods. While effective, their performance can be impacted by complex water chemistries and the presence of co-contaminants. Foam fractionation and colloidal activated carbon (CAC) also operate at high

TRLs and are particularly well-suited for environmental waters, offering efficient PFAS removal with minimal pre-treatment and strong field validation.

Emerging adsorbents, such as surface-modified clays, polymer-coated sand, and biochar, are in the pilot or lab-scale phase (TRL 4–6). These materials show promise but require further demonstration to support full-scale deployment. Destructive technologies, including electrochemical oxidation, sonolysis, plasma, supercritical water oxidation (SCWO), and high-energy electron beam (eBeam), have demonstrated high PFAS degradation in controlled settings and are advancing toward pilot-scale use (TRL 5–7). Advanced reduction processes such as solvated electrons and alkaline hydrothermal treatment remain in early development (TRL 3–5), offering potential for both in situ and ex situ applications. Biodegradation is the least mature (TRL 1–3), with limited and inconsistent results to date.

In PFAS-contaminated soils, treatment options are more limited and primarily applied ex situ, with varying levels of maturity. Excavation and disposal is a fully field-implemented solution (TRL 9), widely used to remove source zones. While effective at eliminating contamination from the site, it does not destroy PFAS and may contribute to landfill leachate. Stabilizing agents can be added prior to disposal to reduce leachability, and in some cases, soils may be treated on site using sorption or thermal methods before reuse or disposal.

Sorption and stabilization/solidification is also field-implemented (TRL 8–9), using amendments such as activated carbon or modified clays to immobilize PFAS and reduce leaching. While effective for containment, these methods do not destroy PFAS and may limit future treatment options, particularly in situ. Soil washing is a field-demonstrated technology (TRL 7–8) that separates PFAS-rich fine particles from reusable coarse fractions, reducing disposal volumes and enabling more targeted treatment. Removal efficiencies for PFOS and other PFAS compounds have exceeded 90% in coarse fractions, with total volume reductions over 90%.

Phytoremediation of PFAS-contaminated soils is currently at TRL 4–5: it has been validated at the lab-scale and in small-scale field experiments, but not yet widely deployed or optimized for full-scale remediation. Phytoremediation has been shown to be a promising technology for shorter-chain PFAS, but even hyperaccumulating crops would take decades to remove longer-chain PFAS from soils.

Thermal treatment, including desorption, incineration, pyrolysis, and gasification, ranges from pilot-scale to field-demonstrated (TRL 6–8), depending on the method. While thermal treatments are already used to treat PFAS wastes (e.g., incineration) they have a TRL of 8 because of uncertainties regarding their effectiveness for totally destroying PFAS. These high-temperature processes offer one of the few potential pathways for permanent PFAS destruction, with removal rates >99%. However, they are energy-intensive and require careful management of emissions and by-products such as hydrogen fluoride. Other destruction technologies although promising have TRLs typically of 7 or less and cannot therefore be currently implemented on Jersey. SCWO has a TRL of 8 but is also energy intensive. Other in situ soil treatments such as electrokinetic remediation remain at a low TRL of 3-4.

Across both water and soil applications, site-specific evaluation and sustainability considerations are critical to ensure effective and responsible remediation. While several technologies are ready for deployment, many others are still evolving. Continued research, pilot testing, and regulatory alignment will be essential to advancing PFAS treatment and achieving long-term environmental protection. As PFAS regulations evolve, especially for short-chain compounds and precursors, treatment selection must remain adaptive. Technologies with scalable deployment and proven field performance will be critical for meeting emerging standards and stakeholder expectations.

Table 2: Summary of PFAS treatment technologies for environmental waters

Technology Category	Example Methods	TRL Range	Primary Function
Sorption	Granular Activated Carbon (GAC), Ion Exchange (IX), Colloidal Activated Carbon (CAC)	8–9	Separation/Immobilization
Emerging Sorbents	Polymer-Coated Sand, Surface-Modified Clays, Biochar, Fluorogels	4–6	Separation/Immobilization
Membrane Filtration	Nanofiltration, Reverse Osmosis	8–9	Separation
Interface-Driven Separation	Foam Fractionation, Water Aggregation and Separation (WAS), Electrocoagulation	6–8	Separation/Concentration
Chemical Oxidation	Ozone-Based Systems, Catalyzed Hydrogen Peroxide (CHP), Activated Persulfate	5–7	Partial Destruction
Advanced Oxidation	Sonolysis, Photochemical Oxidation	6–7	Destruction
Electrochemical Treatment	Boron-Doped Diamond Electrodes	5–7	Destruction
Advanced Reduction	Solvated Electrons, Alkaline Hydrothermal Treatment (HALT)	3–5	Destruction
Plasma Technology	Nonthermal Plasma Systems	5–7	Destruction
Radiation-Based Treatment	High-Energy Electron Beam (eBeam)	5–7	Destruction
Supercritical Oxidation	Supercritical Water Oxidation (SCWO)	6–8	Destruction
Biodegradation	Microbial/Fungal Processes	1–3	Partial Transformation

Table 3: Summary of PFAS treatment technologies for soils

Technology Category	Example Methods	TRL Range	Primary Function
Excavation and Disposal	Identification of hotspots followed by physical excavation, disposal in landfills and in some cases thermal treatment ex-situ	9	Physical removal of contaminated soil followed by disposal/destruction
Soil Washing	Physical excavation followed by soil washing with mechanical separation and chemical extraction	7-8	Remove PFAS-rich fine particles and reduce disposal volume
Sorption and Stabilisation	Sorption/stabilisation in situ with activated carbon, modified clays, cementitious binders	8–9	Reduce PFAS leachability and mobility

Phytoremediation	Planting hyperaccumulating crops in contaminated soils, harvesting crops followed by thermal treatment	4–5	Harvesting removes PFAS taken up into stems/leaves from root zone in soils
Thermal Treatment	Incineration, pyrolysis, gasification (usually ex-situ but some in-situ methods have been tested at lab-scale)	6–8	Permanently destroy PFAS through high-temperature processes
Electrokinetic remediation	Low-voltage electric field applied to mobilize PFAS through soil toward electrodes.	3–4	Destruction not effective for longer-chain PFAS

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Borehole level treatment approaches

Regulatory and standard-setting context for small supplies

In April 2024 the United States Environmental Protection Agency (EPA) identified Best Available Technologies (BAT) and Small System Compliance Technologies (SSCTs) for small public water systems. These focus on granular activated carbon (GAC), ion-exchange (IX) and reverse osmosis/nanofiltration (RO/NF), and they set out indicative design and cost ranges that translate well to borehole and well applications (U.S. Environmental Protection Agency, 2024a, 2024b).

For small groundwater supplies, what ultimately matters is the concentration achieved in the treated water against the statutory limit. Certification marks on individual devices show that a product has met a performance target in a standardised laboratory challenge water; however, legal compliance is demonstrated by sampling the finished water under local conditions. In other words, certification is a useful baseline, but site-specific monitoring is the arbiter of performance (U.S. Environmental Protection Agency, 2024b). Similar approaches apply in the UK and EU.

Core technologies and comparative performance in groundwater

Granular / block activated carbon (GAC/CB)

Mechanism

Activated carbon removes PFAS primarily by adsorption: molecules are held on the carbon surface through a combination of hydrophobic interactions, electrical (electrostatic) effects and pore-filling within the carbon's microstructure. As a rule of thumb, the longer the PFAS molecule's fluorinated "tail", the more strongly it adsorbs. For a given carbon this typically follows PFOS > PFOA > short-chain perfluoroalkyl carboxylic acids (PFCAs). Natural organic matter in groundwater; measured as dissolved organic carbon (DOC); and other dissolved substances can compete for adsorption sites, reducing effective capacity(Appleman et al., 2014; McCleaf et al., 2017).

Performance at small scale

EPA's BAT/SSCT synthesis and numerous bench and pilot studies show that GAC performs well for long-chain PFAS when the empty-bed contact time (EBCT) is adequate. By contrast, shorter-chain compounds such as PFBA, PFPeA and PFHxA tend to pass through the bed earlier ("breakthrough"), a tendency that is accelerated when DOC is higher. To manage this, small systems typically install two vessels in series (lead–lag) and use "sentinel" monitoring to detect rising concentrations before the second vessel is affected (Pannu et al., 2023; U.S. Environmental Protection Agency, 2024b). Column studies and rapid small-scale column tests (RSSCTs) conducted on multiple groundwaters reproduce this pattern reliably, confirming that breakthrough is strongly dependent on chain length and local water chemistry (Hopkins & Knappe, 2024; McCleaf et al., 2017; Pannu et al., 2023).

Co-contaminants and pretreatment

Groundwaters with elevated iron, manganese or turbidity can foul carbon beds, while higher DOC reduces adsorption capacity. Alkalinity (e.g., bicarbonate) can also influence adsorption kinetics. For these reasons, small systems commonly include pre-filtration or oxidation upstream of the PFAS step so that the carbon bed sees cleaner water and lasts longer (U.S. Environmental Protection Agency, 2024a).

Ion-exchange resins (IX)

Mechanism

Anion-exchange resins remove PFAS through electrostatic attraction to positively charged functional groups (typically quaternary ammonium) and through hydrophobic partitioning into the resin matrix. Resin performance is sensitive to the resin's chemistry and structure (e.g., gel vs macroporous). Competing anions such as sulphate and bicarbonate can occupy exchange sites and reduce the effective capacity for PFAS (Chow et al., 2022; U.S. Environmental Protection Agency, 2024b).

Performance at small scale.

Parallel pilot trials and RSSCTs generally show that IX outperforms GAC for short-chain PFCAs at comparable EBCT. In practice this means longer run-lengths before breakthrough, while still achieving near-complete removal of long-chain PFAS at the start of a run. Many small systems opt for single-use resins to avoid handling brine; the trade-off is higher media cost. Where regenerable operation is chosen, the resulting PFAS-bearing brine must be managed carefully and may need polishing or destruction before disposal (Chow et al., 2022; Pannu et al., 2023; U.S. Environmental Protection Agency, 2024b).

Reverse osmosis / nanofiltration (RO/NF)

Mechanism

RO and tight NF are membrane separation processes. Water is pushed through thin-film composite membranes; dissolved contaminants are largely held back based on size and charge. Pre- and post-carbon stages in packaged units manage chlorine (to protect the membrane), taste and residual organics.

Performance at small scale

Packaged RO systems ("skids") routinely achieve > 90–99 % rejection across long- and many short-chain PFAS, with treated water often at or near analytical detection limits when membranes are intact and pretreatment is adequate (Appleman et al., 2014; Tow et al., 2021). Tight NF can approach RO performance for longer chains while achieving higher water recovery, but shows greater variability for short-chain PFASs (Tow et al., 2021). A practical consideration is the concentrate (reject) stream; commonly 15–50 % of the feed depending on the chosen recovery and fouling control; which needs a responsible management route (Tow et al., 2021; U.S. Environmental Protection Agency, 2024a).

Foam fractionation (FF) and destructive add-ons (for side-streams)

Foam fractionation exploits the surfactant-like behaviour of many PFAS. Air is bubbled through water, PFAS partition into the rising foam, and the foam is skimmed off. Trials show particularly strong removal for long-chain sulphonates (often > 80–95 %), with lower capture for ultrashort and short chains (Smith et al., 2023; Y. Wang et al., 2023). At small scale, FF is best used either upstream to lower the load on GAC or IX, or applied to RO/NF concentrate so that a smaller side-stream carries most of the PFAS mass prior to disposal or destruction (Smith et al., 2023; Y. Wang et al., 2023).

Destructive technologies; including electrochemical oxidation (EO) and UV-advanced reduction processes (UV/sulphite or UV/iodide); are generally applied to these smaller side-streams (concentrates and regenerant brines) rather than the full flow. Laboratory and pilot studies are promising, but energy demand, by-product management and scale-up for routine drinking-water use remain active research challenges (Fennell et al., 2022; Yifei Wang et al., 2023).

Design approaches for borehole and well supplies

Wellhouse point-of-entry (POE) adsorption

GAC trains

A typical arrangement uses two or more pressure vessels in lead–lag with sampling taps between the vessels. This set-up provides early warning of breakthrough and protects the final outlet. At small scale, EBCTs often sit in the upper single-digit to low double-digit minutes per vessel, constrained by flow and available space. Change-out triggers are usually based on a short-chain "sentinel" PFAS at conservative ng/L levels well below any regulatory limit, so that the second vessel is never compromised (Hopkins & Knappe, 2024; U.S. Environmental Protection Agency, 2024b).

IX trains

PFAS-selective strong-base resins arranged in lead–lag offer robust control of short-chain PFAS at EBCTs similar to GAC. Choosing single-use operation simplifies operation and maintenance by removing brine handling, at the expense of media cost. Regenerable systems can be cost-effective on media, but they introduce the need to collect, treat and dispose of PFAS-bearing brine responsibly (Chow et al., 2022; U.S. Environmental Protection Agency, 2024b).

Selection logic

Where the groundwater contains mostly long-chain PFAS and DOC is low, appropriately sized GAC can meet very low ng/L targets at a reasonable cost. Where short-chain PFAS are prominent, or DOC and sulphate are elevated, IX tends to deliver longer bed lives before breakthrough. In all cases, pilot testing or RSSCTs conducted on the actual groundwater are the preferred basis for selecting media and fixing bed size (Chow et al., 2022; Hopkins & Knappe, 2024; Pannu et al., 2023; U.S. Environmental Protection Agency, 2024b).

Membrane skids (RO/NF)

Small-system RO/NF is supplied as a compact skid with cartridge pre-filters (typically 1–5 µm), antiscalant dosing or upstream softening, and periodic clean-in-place (CIP). Typical groundwater recoveries are around 50–85 %, depending on hardness, silica and fouling tendency. Concentrate can be discharged to sewer (where permitted), stored and transferred off-site, or processed further; often using FF or IX/GAC; to reduce volume before final management. Membrane integrity is monitored with salt-rejection trends and periodic targeted PFAS analyses (Tow et al., 2021; U.S. Environmental Protection Agency, 2024b).

Household-level backstops on private wells

Where a single borehole serves one property, point-of-entry adsorption or point-of-use RO at the building can add resilience. Studies on private wells show point-of-use RO consistently achieves near-detection PFAS concentrations across a broad range of compounds, while point-of-entry adsorbers work well if cartridges are replaced before short-chain breakthrough. The same influencing factors: DOC, sulphate/alkalinity, iron and manganese: apply, albeit at lower flows than community systems (Appleman et al., 2014; Herkert et al., 2020).

Monitoring, operations and residuals

Sentinel monitoring with lead/lag. For adsorption systems, inter-vessel taps allow routine measurement of early-runner PFAS (often PFHxA/PFBA) so that bed change-out happens before the finished water rises. The sampling frequency should be proportional to throughput (expressed as bed volumes) and to any upward trend seen in monitoring data (Hopkins & Knappe, 2024; U.S. Environmental Protection Agency, 2024b). For membranes, continuous conductivity or periodic salt-rejection checks alongside targeted PFAS analyses provide assurance of membrane integrity (Tow et al., 2021).

Matrix management

DOC suppresses GAC performance; sulphate and bicarbonate compete on IX; and hardness, iron and manganese foul both adsorbers and membranes. As a result, many small systems incorporate pre-filtration and oxidation, and, where membranes are used, antiscalants or softening, to control the matrix and keep the PFAS step operating within design assumptions (U.S. Environmental Protection Agency, 2024a, 2024b).

Residuals

All capture-based processes move PFAS from water into a smaller mass of spent media or a concentrate/brine. Spent GAC may be thermally reactivated (with PFAS destruction managed by the reactivator). Single-use resins are typically disposed of as solid waste in accordance with local rules. Regenerant brines and RO/NF concentrates need their own management pathway. A growing practice is to pre-concentrate with FF, then apply EO or a UV-advanced reduction process to destroy PFAS in that smaller stream rather than tackling the full flow (Fennell et al., 2022; Yifei Wang et al., 2023; Y. Wang et al., 2023).

Analytical conclusions for borehole/well treatment

- Separation remains the backbone. GAC, IX and RO/NF are the proven mainstays for small supplies. Conventional coagulation and media filtration do not reliably remove PFAS unless a dedicated separation step is added (Appleman et al., 2014; U.S. Environmental Protection Agency, 2024b).
- Short-chains (where relevant) set the replacement clock. Meeting single- and low-double-Short-chains (where relevant) set the replacement clock. Achieving single- and low double-digit ng/L targets in mixed PFAS plumes typically calls for IX tuned to short-chains (with attention to competing anions) or RO/NF with appropriate pretreatment

and concentrate management. GAC is well-suited where long-chains dominate and EBCT is adequate at low DOC (Chow et al., 2022; Pannu et al., 2023; Tow et al., 2021).
- Local pilot/RSSCT data should govern sizing. Because DOC, sulphate and alkalinity vary widely between groundwaters, "copy-and-paste" designs frequently misjudge run-lengths by orders of magnitude. Site-specific testing should be used to set EBCT, bed volumes, flux/recovery and change-out triggers with confidence (Hopkins & Knappe, 2024; U.S. Environmental Protection Agency, 2024b).
- Hybrids reduce risk and O&M. Common small-system trains include IX → GAC (to pair short-chain control with polishing of organics) and RO/NF with FF on the concentrate (to shrink the destruction/disposal problem). These combinations are increasingly documented in recent pilots and reviews (Smith et al., 2023; Tow et al., 2021; Y. Wang et al., 2023).

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Domestic appliances for reducing PFAS in drinking water

There are arrange of technologies and appliance types for lowering the level of PFAS in a residential setting. This section explores the range of these technologies, their relative strengths and limitations, and any additional benefits relating to other pollutants.

Regulatory and certification context relevant to household devices

In practice, North American standards define the benchmark used worldwide. The relevant device standards are NSF/ANSI 53 (adsorptive/ion-exchange filters) and NSF/ANSI 58 (reverse osmosis). A legacy protocol, NSF/ANSI P473, verified reduction of PFOA/PFOS; in 2022 its scope was folded into 53/58 and expanded to a “Total PFAS” claim covering a multi-compound mixture with a combined treated-water limit of 20 ng/L (down from the earlier 70 ng/L criterion that applied to PFOA+PFOS alone). Certification is issued by ANSI-accredited bodies; notably NSF, IAPMO, WQA, UL, and CSA; and products are listed in public directories. (NSF International, 2024)

The U.S. EPA (2024–2025) points consumers and utilities to those certifications and notes that current device standards are being updated in light of the new federal MCLs (PFOA/PFOS at 4 ng/L; PFHxS, PFNA, HFPO-DA at 10 ng/L, plus a hazard-index approach). EPA also aggregates links to the five ANSI-accredited certifier directories. In short: device certifications validate reduction performance under standard challenge waters, while regulatory MCLs set health-based finished-water goals for systems; the two are related but distinct. (U.S. Environmental Protection Agency, 2024a, 2024b, 2025)

In the EU, the UK, and Australia, while there are regulations for PFAS in drinking water, there are no specific standards for PFAS-specific appliance performance standards.

Two implications follow. First, certification end-points (≤ 70 ng/L for PFOA/PFOS in legacy tests; ≤ 20 ng/L combined under “Total PFAS”) are performance thresholds for devices, not health limits. Second, as device certifications evolve, short-chain PFAS coverage has improved in test protocols, but field performance under diverse matrices still shows variability. (MacKeown et al., 2024)

Different technologies in use

Granular and block activated carbon (GAC/CB)

Mechanism. Adsorption via hydrophobic interactions, electrostatics, and pore-filling on high-surface-area carbon. Performance increases with perfluoroalkyl chain length and aromaticity; competition from dissolved organic carbon (DOC) and co-solutes reduces capacity. (Zhang et al., 2021)

Comparative performance. Multiple studies report higher removal for long-chain PFAS (e.g., PFOS, PFOA) than for short-chain species (e.g., PFBS, PFBA). Equilibrium and column studies consistently show chain-length-dependent sorption (PFOS > PFOA > PFBS > PFBA). Breakthrough of short-chain acids can occur early at realistic empty-bed contact times (EBCT), particularly at elevated DOC. (Zhang et al., 2021)

Household evidence. In a national assessment of POU devices, activated-carbon systems reduced PFAS variably; long-chain compounds were attenuated more reliably than short-chains, while RO reduced broader suites to near or below detection. (Herkert et al., 2020) A 2024 controlled evaluation of pitcher-type carbon/IX cartridges across two waters (Σ_{75} PFAS = 13 and 56 ng/L) found wide variability among designs and rapid capacity loss for some configurations, underscoring the importance of contact time and media dosage in gravity formats. (Teymoorian et al., 2024)

Co-contaminants. Carbon is effective for many organic micropollutants (e.g., VOCs, some "401" compounds) and for taste/odour, but has little effect on inorganics such as nitrate or fluoride. (U.S. Environmental Protection Agency, 2024a)

Ion-exchange (IX) resins

Mechanism. Strong-base or specialized resins exchange counter-anions and adsorb PFAS via electrostatic and hydrophobic interactions; quaternary ammonium functional groups and matrix hydrophobicity strongly influence selectivity. (Chow et al., 2022)

Comparative performance. Pilot and column studies often show longer breakthrough times and higher capacities for IX than GAC under PFAS-impacted waters, including scenarios dominated by short-chain PFCAs, though resin chemistry matters. Structure selectivity work suggests tailored long-chain amine resins can improve uptake across PFAS classes. (Chow et al., 2022)

Household relevance. In POU cartridges, IX is commonly blended with carbon to widen the spectrum. Field/bench evidence indicates improved short-chain control relative to GAC alone, but exhaustion can still be rapid when influent concentrations or DOC are high. (Chow et al., 2022)

Co-contaminants. IX can target some anionic species, but selectivity for common inorganics is limited; pairing with carbon is typical to address organics not well retained by IX. (Chow et al., 2022)

Reverse osmosis (RO) and nanofiltration (NF)

Mechanism. Size- and charge-based exclusion through thin-film composite membranes; pre-post-carbon stages in consumer units primarily handle chlorine, organics, and taste. (Tow et al., 2021)

Comparative performance. Point of use (POU)/under-sink RO frequently achieves **>** 90–99 % rejection across long- and many short-chain PFAS, with treated water at or near instrument detection in lab/field tests. NF performance is more membrane-dependent (reported ≈ 70–99 %); "tighter" NF/RO improves short-chain rejection at the cost of flux. (Mulhern et al., 2021; Tow et al., 2021)

Household evidence. In a cross-sectional POU study, RO was the most consistent technology across PFAS spanning legacy and emerging compounds; two-stage/RO configurations reduced PFAS (including HFPO-DA) by ≥ 94 % (study-specific conditions). A 2024/2025 synthesis similarly found average POU removals > 90 % for RO. (Herkert et al., 2020)

Co-contaminants and trade-offs. RO reduces dissolved inorganics (e.g., nitrate, fluoride, arsenic), but generates a concentrate stream; typical residential recoveries are on the order of 20–45 %, varying by design. Membrane scale/clogging risk rises with hardness and particulates; prefiltration is standard. (Tow et al., 2021)

Deployment formats and engineering constraints

Point-of-entry (POE; whole-house)

Typical technologies. Large-bed GAC/CB systems, sometimes with IX media; RO is rarely deployed at whole-house flow because of recovery/pressure constraints.

Relative PFAS performance. POE carbon/IX can attenuate long-chain PFAS effectively and; in optimized beds; control selected short-chains, but breakthrough behaviour depends strongly on influent composition, DOC, and EBCT. Certified POE offerings historically referenced the PFOA/PFOS protocol (≤ 70 ng/L), with fewer publicly documented POE "Total PFAS" certifications to date. Verification sampling to detect onset of breakthrough is central at POE scale. (Kucharzyk et al., 2017)

Operational constraints. High volumetric throughput reduces contact times; media change-out is driven by loading (ng of PFAS per g of media), not merely by months of use. Waste management of spent beds (PFAS-laden carbon/resin) and safe handling are additional considerations. (Chow et al., 2022)

Co-contaminants. POE carbon commonly targets chlorine/chloramine and some VOCs; pairing with softening/iron-manganese control is routine for non-PFAS objectives. (Concawe, 2020)

Under-sink point-of-use (POU; plumbed)

Typical technologies

- Composite CB/IX cartridges
- RO with pre-/post-carbon polishing.

Relative PFAS performance.

- **CB/IX**: Reliable for long-chain species; short-chain performance is medium-to-high but more sensitive to EBCT and matrix chemistry (DOC, sulphate, bicarbonate). Peer-reviewed pilot work shows IX > GAC for many cases, particularly short-chains, with longer breakthrough times in parallel columns. (Chow et al., 2022)
- **RO**: High rejection of both long- and many short-chains, often producing permeate near detection at the tap; performance depends on membrane integrity and pre-treatment. (Tow et al., 2021)

Operational constraints.

- **CB/IX**: Cartridges sized for hundreds–thousands of litres typically; replacement triggers should reflect both volume and time because adsorption is capacity-limited and susceptible to fouling.
- **RO**: Separate lifetimes for prefilters (months) and membranes (1–2 years are commonly reported in technical literature); permeate recovery can be 20–45 %. (Tow et al., 2021)

Co-contaminants. CB/IX excels for organics/lead (when certified under 53/401), while RO additionally addresses dissolved inorganics (nitrate, fluoride, arsenic). (U.S. Environmental Protection Agency, 2024a)

Worktop POU (plug-in RO and non-RO cartridges)

Typical technologies

- **Plug-in RO** with internal reservoirs
- **non-RO** counter units using CB/IX.

Relative PFAS performance.

- **Worktop RO** mirrors under-sink RO in membrane rejection, with the advantage of no plumbing
- **non-RO** countertop cartridges show PFAS performance similar to under-sink CB/IX provided contact time is adequate.

Comparative household studies consistently place RO at the high end of PFAS removal under mixed influent. (Herkert et al., 2020)

Operational constraints.

- Worktop RO designs manage concentrate internally but still discharge periodic flush volumes;
- non-RO designs depend critically on flow control (contact time). (Tow et al., 2021)

Pitcher/gravity ("filter jugs")

Typical technologies. Carbon blocks and/or blended CB + IX in gravity flow.

Relative PFAS performance. Pitchers can reduce PFOA/PFOS and some short-chains, but performance is highly variable among designs, with faster exhaustion under high TDS/DOC waters. A 2024 evaluation across two waters showed compound-specific removal spanning from near-complete for some long-chains to modest for several short-chains; and with rapid declines in some configurations as capacity was consumed. (Teymoorian et al., 2024)

Operational constraints. Low head pressure limits EBCT and mass transfer; tens–hundreds of litres per cartridge are typical order-of-magnitude capacities in the literature and public health summaries, with change-outs required to sustain certified performance. (U.S. Environmental Protection Agency, 2024a)

Summary table

Deployment format	Dominant household technology	Mechanistic strength vs PFAS	Typical relative performance (long-chain → short-chain)	Major operational constraints	Co-contaminant profile (typical)
POE (whole-house)	**Large-bed GAC/CB, sometimes IX**	Adsorption with EBCT-dependent capacity; IX improves anionic selectivity	High → medium (GAC/CB); high with IX for some short-chains; breakthrough governed by	High flow lowers contact time; media change-out driven by ng PFAS /g verification sampling critical	Organics (VOC/T&O) via carbon; minerals largely unchanged

Deployment format	Dominant household technology	Mechanistic strength vs PFAS	Typical relative performance (long-chain → short-chain)	Major operational constraints	Co-contaminant profile (typical)
			loading and DOC		
Under-sink POU (non-RO)	**Composite CB/IX**	Adsorption/ion-exchange; better residence time than pitchers	High → medium; IX improves short-chain control vs GAC alone	Capacity-limited; hundreds–thousands of litres typical order of magnitude; performance sensitive to DOC	Lead/VOCs (when 53/401); little effect on nitrate/fluoride
Under-sink POU (RO)	**RO + pre/post carbon**	Size/charge exclusion across TFC membrane	Very high → high across many PFAS (including HFPO-DA), often near MDLs	Concentrate stream (20–45 % recovery), membrane scaling/fouling; periodic filter/membrane replacement	Broad inorganic and organic reduction (nitrate, fluoride, arsenic; with carbon polishing)
Worktop POU (RO)	**RO**	Same as above	Very high → high	Internal reservoir; periodic flushes; electrical needs	Similar to under-sink RO
Worktop POU (non-RO)	**CB/IX**	Adsorption/IX with controlled flow	High → medium (design-dependent)	Cartridge capacity; design-specific flow control	Organics and some metals; not salts
Pitcher/gravity	**CB** or **CB + IX**	Low-pressure adsorption; short contact times	Moderate → variable; best on long-chains; short-chains often lower and degrade with use	Tens–hundreds of litres order of magnitude; rapid performance decline possible	Taste/odour; some organics; minimal effect on inorganics

Key findings from comparative analysis

- Chain-length dependence is fundamental. Carbon sorption favours long-chain PFSAs/PFCAs (PFOS, PFOA, PFNA) over short-chains (PFBS, PFBA); early carbon column work and subsequent equilibrium studies report consistent isotherm trends and faster short-chain breakthrough at realistic empty bed contact times (EBCTs). (Yu et al., 2009)

- IX generally outperforms GAC for short-chains. A 441-day parallel pilot demonstrated longer run times and higher short-chain PFCA removal with strong-base IX resins than GAC under groundwater conditions; resin chemistry and water matrix (e.g., sulphate) modulate selectivity. (Chow et al., 2022)
- RO is the most broadly effective single technology at POU scale. Multiple syntheses and field campaigns find > 90–99 **%** rejection across PFAS suites, including many short-chains, with permeate often near the method detection limits when membranes are intact and pretreatment is adequate. NF can approach RO performance with tight membranes but is more variable for short-chains. (Tow et al., 2021)
- Pitcher performance is design-specific and can degrade quickly. Gravity cartridges show wider variance across brands/models and rapid capacity loss in some cases; studies that tracked removal across dozens of PFAS in real tap waters document divergent outcomes across products in the same water, emphasizing the centrality of media mass and flow control. (Teymoorian et al., 2024)
- Field vs. bench. Cross-sectional sampling of households (multiple U.S. states) found RO consistently reduced PFAS to near or below detection, whereas carbon-based POU performance ranged from moderate to high and depended on water chemistry and compound class. Longitudinal monitoring of carbon POU on private wells showed initial high removal followed by compound-specific breakthrough, reinforcing the need to link replacement intervals to exposure rather than elapsed time alone. (Herkert et al., 2020)
- Certification targets vs. MCLs. Devices certified to legacy PFOA/PFOS criteria must achieve ≤ 70 ng/L under a 1 500 ng/L challenge; “Total PFAS” devices must achieve ≤ 20 ng/L combined under a 2 160 ng/L mixture. These thresholds are not identical to 2024 EPA MCLs, which are lower for some compounds (e.g., PFOA/PFOS at 4 ng/L). Accordingly, even a certified device may produce effluent below the certification threshold but above an MCL in challenging matrices—or below MCLs in favourable matrices—depending on design and maintenance. (Washington State Department of Health, 2025)

Unresolved issues, by technology and format

- **Short-chains and ultrashort-chains.** While RO/NF can substantially reject C2–C6 acids and sulphonates under optimized conditions, the most mobile ultrashort-chains remain analytically and operationally challenging. Adsorption requires long EBCT and tailored sorbents; recent material science (e.g., specialized IX and advanced adsorbents) shows promise but limited household validation.
- **Matrix effects.** DOC and competing anions (sulfate, bicarbonate) reduce IX capacities and impede GAC sorption; hardness and colloids impact RO via scaling and fouling, increasing the need for pretreatment and maintenance.
- **By-products and integrity.** Thin-film composite membranes can contain fluorinated materials; a 2024 analysis cautioned about potential PFAS leaching from certain membrane constructions, though operational significance at POU scale remains under investigation. (Sadia et al., 2024)
- **Residue management.** All capture-based methods (GAC, AIX, RO/NF) transfer PFAS to a spent medium or concentrate requiring disposal. Household guidance typically directs spent

cartridges to solid waste; POE operations may require managed disposal or regeneration with brine waste handling. (Concawe, 2020)

- **Certification scope vs. real-world mixtures.** The seven-analyte "Total PFAS" mixture does not encompass all field-relevant PFAS (e.g., precursors); nor do certification waters always reflect local DOC/ionic strength. As a result, certified performance is a necessary but not sufficient indicator of field removal for every mixture. (Washington State Department of Health, 2025)

Conclusions

- **Mechanism dictates selectivity.** GAC/CB provide robust adsorption for long-chain PFAS but are matrix-limited for short-chains; IX improves short-chain retention but remains capacity-limited. RO most consistently reduces broad PFAS suites (including many short-chains) to low ng/L levels, with a concentrate-stream trade-off.

- **Format governs contact time and reliability.** Under-sink plumbed systems (CB/IX or RO) achieve better residence times and control than pitchers, which show wide variability and faster exhaustion. Countertop RO offers RO-level rejection without plumbing but with reservoir/flush considerations. POE carbon/IX can protect all taps but requires careful sizing and verification monitoring for breakthrough. (Teymoorian et al., 2024)

- **Certification end-points and MCLs are not the same.** Devices meeting ≤ 20 ng/L combined ("Total PFAS") or ≤ 70 ng/L (legacy PFOA/PFOS) under standardized challenges may or may not deliver ≤ 4–10 ng/L under site-specific conditions; nonetheless, certifications provide comparable, audited baselines for performance claims. (Washington State Department of Health, 2025).

- **There is no domestic technology that is certified to reduce PFAS to the levels the panel has recommended for Jersey**. This, of course, does not mean that the appliances are not capable of such a reduction.

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