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Literature Review of Adsorbents for PFAS Removal from Groundwater

NESDI Project #578
Task 1

Nicholas T. Hayman
Jessica E. Carilli
Robert D. George
Lewis Hsu
Melissa A. Sanders
NIWC Pacific

Yina Liu, Michael Shields
Texas A&M University

Becca Morrison
San Diego State University Research Foundation

Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001

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NIWC Pacific
San Diego, CA 92152-5001

NIWC Pacific
San Diego, California 92152-5001

A. D. Gainer, CAPT, USN
Commanding Officer

W. R. Bonwit
Executive Director

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Released by
John deGrassie, Division Head
Basic and Applied Research

Under authority of
Carly Jackson, Department Head
Cyber Science and Technology

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EXECUTIVE SUMMARY

Per- and polyfluorinated alkylated substances (PFAS) are a diverse group of chemicals that are widespread in groundwater including at US Navy and US Marine Corps sites. These chemicals are very stable in the environment and motile. These contaminants pose human and environmental health concerns and, as such, the EPA has issued drinking water lifetime health advisories for PFOA (a perfluorocarboxylic acid [PFCA]) and PFOS (a perfluoroalkyl sulfonic acid [PFSA]) at 70 ng/L (70 parts per trillion). Due to this, remediation of these chemicals represents a significant financial liability for the Department of Defense (DoD), including the US Navy. The DoD has invested millions of dollars to develop technologies to mitigate PFAS contamination in groundwater.

One of the most developed technologies for treating contaminants in water and sediments are various sorbent materials; these materials bind contaminants such that they are no longer bioavailable and thus do not pose health hazards. This review presents the state of the science of sorbent materials in PFAS remediation, and was used to guide the implementation of laboratory and field-based experiments focused on selecting appropriate sorbents to treat contaminated ground water *in situ* (i.e. treatment is deployed in the impacted groundwater system) for NESDI project #578. The two sorbent materials that are most commonly employed at DoD sites are granulated activated carbon and anion exchange resins. While these have been widely studied and have been somewhat effective for remediating PFOS and PFOA contamination, they have shown less effectiveness for the newer, short-chained PFAS constituents. While there has been a lot of research focus on developing more effective sorbents, many of these are still in development and not ready for the remedy implementation testing that will be conducted for this NESDI project. Some of these novel sorbents under development are described in this review. In addition, this review includes a discussion addressing gaps in the literature, including the need for simultaneous study of the efficacy of multiple sorbents to remove PFAS from water with varying water quality characteristics as well as in-the-field testing. The review ends with a table summarizing groundwater characteristics at Navy sites from the PFAS library data, illustrating the range of conditions to which an *in situ* sorbent treatment would be subjected.

ACRONYMS

AFFF	Aqueous Film-Forming Foam
AIX	Anion Exchange Resin
CAC	Colloidal Activated Carbon
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
DMAPAA-Q	N-[3-(Dimethylamino)propyl] Acrylamide, Methyl Chloride Quaternary Hydrogel
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
GAC	Granulated Activated Carbon
MCL	Maximum Contaminant Levels
NESDI	Naval Environmental Sustainability Development to Integration Program
NOM	Natural Organic Material
PAC	Particulate Activated Carbon
PFAA	Perfluoroalkyl Acids
PFAS	Per- and polyfluoroalkyl Substances
PFOA	Perfluoro-n-Octanoic Acid
PFCA	Perfluorocarboxylic Acid
PFOS	Perfluorooctanesulfonic Acid
PFSA	Perfluoroalkyl Sulfonic Acid
P&T	Pump and Treat
SERDP	Strategic Environmental Research and Development Program
TFN-CDP	Tetrafluoroterephthalonitrile

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1. INTRODUCTION

Per- and polyfluorinated alkylated substances (PFAS) are a diverse group of chemicals that are widespread in groundwater systems including at US Navy and US Marine Corps sites. As of 2017, approximately 127 installations have known or suspected releases of PFAS, impacting more than 750 groundwater wells that have been sampled to date, due largely to their use in some firefighting foams (specifically, AFFF [aqueous film-forming foam]). In the environment, under relevant biological conditions, some PFAS (called "precursors") transform into a specific PFAS class, the perfluoroalkyl acids (PFAA). These contaminants are human and environmental health concerns and, as such, the Environmental Protection Agency (EPA) has issued drinking water lifetime health advisories for two PFAAs: PFOA (a perfluorocarboxylic acid [PFCA]) and PFOS (a perfluoroalkyl sulfonic acid [PFSA]) at 70 ng/L (70 parts per trillion). These compounds, as well as their precursors and other PFAS, are common components of AFFF formulations. Seven states have independently set their own lifetime health advisory guidelines for these pollutants at lower values (ranging from 5-70 ng/L), including states with Navy facilities such as California. In fact, as of August 2019, California has set its drinking water notification levels at 6.5 ng/L for PFOS and 5.1 ng/L for PFOA, effectively at detection limits for current analytical methods (CWB 2019). In addition, the EPA is currently determining official maximum contaminant levels (MCL) for these, as well as other, PFAS constituents. Unlike the heath advisory guidelines and notification levels, MCL exceedance would result in mandated regulatory action and represent significant liability for the Navy. As such, proactive efforts to remediate groundwater, especially when used as a source of drinking water, are critical.

Currently, Navy facilities are primarily using pump and treat (P&T) technology with granulated activated carbon (GAC) to remove PFAS from groundwater. While this method has proven somewhat effective, it does require frequent (on the order of months) and costly GAC replacement (it cannot be regenerated) and there is evidence that GAC does not work as well on the short-chained PFAS in newer AFFF formulations, which are replacing the longer-chained PFOS and PFOA (Appleman et al. 2014, Xiao et al. 2017, Ross et al. 2018). In addition, the removal of shorter-chain precursor PFAS that can transform into PFAA (e.g. PFOS, PFOA) is becoming an increasing concern; as these precursors are less effectively removed by GAC treatments, they can remain in water returned to the ground and transform downstream into PFAA (e.g. PFOS, PFOA), resulting in continued PFAA contamination that was not detected upstream (Ahrens and Bundschuh 2014).

In situ (i.e. treatment is deployed in the impacted groundwater system) amendments (e.g. activated carbon placed in a trench around a contaminant plume) are currently used to remediate groundwater contamination by other organic contaminants such as solvent spills. A variety of possible sorbents that could be used as in situ treatments for PFAS contamination have been suggested (e.g. GAC, colloidal carbon, biochar, Obsorb®, etc.). However, many of these sorbents have not received sufficient scientific scrutiny to justify large-scale application at Navy facilities, especially considering the wide array of PFAAs (in particular short-chained compounds) and their precursors that exist at Navy sites. In addition, some studies have shown that typical in situ amendments that are effective for other organic contaminants are not always suitable for PFAS, partially due to the high mobility of PFAS in the aqueous phase and recalcitrant properties, especially for the short-chained PFAS (<6 perfluoroalkyl carbons) (Appleman et al. 2014, Dickenson and Higgins 2016). Given the expense to install in situ groundwater amendments, it is critical to ensure that possible sorbents are adequately evaluated before serious consideration of in situ installation. The goal of this literature review is to 1) identify gaps in knowledge of mature adsorbent technologies and describe how NESDI project #578 will address these, 2) identify water quality parameters that affect amendment efficacy, and 3) determine relevant water quality ranges for Navy groundwater sites to aid in environmentally relevant laboratory test design.

2. SORBENTS AND PFAS

PFAS comprise a large group of more than 4,700 human-made chemicals with one or more fully fluorinated alkyl moieties, following the general form of C_nF2_{n+1}, known as the perfluoroalkyl group, many of which have not be characterized (Birnbaum 2018, Buck et al. 2011, Barzen-Hanson et al. 2017, Wang et al. 2017). While there are several sub-groups of these chemicals, those receiving the most attention due to established and suspected environmental and human health risks are the perfluorinated alkyl acids (PFAA) (Conder et al. 2008, 2019, Wang et al. 2017). In general, other PFAS compounds tend to biotransform into PFAA (Ahrens and Bundschuh 2014, Ross et al. 2018). There is no evidence of biodegradation of PFAS in the environment, just biotransformation into the recalcitrant PFAA (Ross et al. 2018). PFAA are particularly recalcitrant (do not easily break down) and are mobile in the environment, including in groundwater, which has led them to be a particularly challenging contaminant to mitigate (as compared to compounds that tend to bind to soil particles, for example, and thus do not disperse as well). PFAA recalcitrance is primarily associated with their C-F bonds, which are difficult to break down and show little natural attenuation, and their amphiphilic (both hydrophilic and lipophilic) characteristics. PFAA are comprised of perfluoroalkyl sulfonic acids (PFSA) or perfluorocarboxylic acids (PFCA), among other chemicals. PFAA are also separated into long-chained (7 or more carbons) or short-chained (6 or fewer carbons) sub-groups (Ahrens and Bundschuh 2014). In general, long-chained PFAA are being replaced by short-chained PFAA in newer materials, as these compounds are less bioaccumulative, but risks to human and ecological health from short-chained PFAA is still a topic of research (Conder et al. 2008, 2019, Wang et al. 2017). For brevity, the remainder of this document will use acronyms to refer to specific PFAA; see Table 1 for reference.

PFAA are comprised of a hydrophilic, anionic functional group, such as the sulfonate in PFSA, and a hydrophobic perfluoroalkyl group. As such, these compounds are highly soluble in freshwater (and less so in brackish and saltwater) (Ahrens and Bundschuh 2014, Ross et al. 2018). Further, due to their amphiphilic characteristics, these chemicals tend to concentrate at surfaces and interfaces (e.g. water/air interface) and give the compounds many of their useful characteristics that have led to their proliferation in commercial products (e.g. surfactant properties, ability repel water, oil, dirt, etc.). PFAA's high solubility, low to moderate sorption to soils, and lack of volatility make them highly mobile in groundwater, resulting in larger water contamination plumes than conventional contaminants (e.g. Ross et al. 2018). It should be noted that PFAS, in addition, include many cationic and zwitterionic constituents, many of which are precursors to PFAA and are either not described or not detectable with current standard methods (Ahrens and Bundschuh 2014, Barzen-Hanson et al. 2017). It is important to consider these constituents in addition to the PFAA in remediation efforts, as these will likely transform and result in PFAA contamination downstream and/or result in an underestimation of the extent of contamination at a given site, although accurate quantitation of these compounds is still a major challenge (Ahrens and Bundschuh 2014, Xiao et al. 2017).

There are several mechanisms that control the degree of PFAA sorption to soil organic particles as well as sorbents used for remediation, such as activated carbon and anion exchange resins. The most important mechanism is hydrophobic sorption (Horst et al. 2018, Ross et al. 2018, Banks et al. 2020). In general, the longer the PFAA molecule, the larger the partitioning coefficients are, resulting in stronger hydrophobic sorption. In addition, PFAA can adsorb to surfaces through electrostatic interactions. As many PFAA are anionic, these electrostatic interactions can be exploited when the sorbent has positively-charged bonding sites (anion exchange resins) and/or a positively charged surface (Banks et al. 2020). As mineral surfaces are generally negatively charged, electrostatic interactions reduce soil sorption, but do contribute to the success of various sorbents with positive surface charge (Du et al. 2014, Stebel et al. 2019, Ateia et al. 2019a). Finally, several studies have found that longer chained PFAA seem to accumulate at higher concentrations than hydrophobic and electrostatic interaction would predict, possibly due to micelle or hemi-micelle formation (essentially, clumping) (Chen et al. 2011, Zaggia et al. 2016, McCleaf et al. 2017, Ross et al. 2018). The effectiveness of a sorbent in removing PFAS is dependent on various parameters including the properties of the sorbent (e.g. pore size, surface charge, functional group, hydrophobicity), the PFAS being removed (e.g. size/shape, functional group, hydrophobicity) and water chemistry (e.g. pH, dissolved organic carbon [DOC], and background inorganic ions) (Kucharzyk et al. 2017, Ross et al. 2018, Banks et al. 2020).

Table 1. List of selected PFAS to be analyzed under NESDI Project #578.

Analyte Name	Abbreviation	CAS Number
Perfluoroalkylcarboxilic Acids (PFCA)		
Perfluoro-n-tetradecanoic acid	PFTeDA	376-06-7
Perfluoro-n-tridecanoic acid	PFTrDA	72629-94-8
Perfluoro-n-dodecanoic acid	PFDoA	307-55-1
Perfluoro-n-undecanoic acid	PFUdA	2058-94-8
Perfluoro-n-decanoic acid	PFDA	335-76-2
Perfluoro-n-nonanoic acid	PFNA	375-95-1
Perfluoro-n-octanoic acid	PFOA	335-67-1
Perfluoro-n-heptanoic acid	PFHpA	375-85-9
Perfluoro-n-hexanoic acid	PFHxA	307-24-4
Perfluoro-n-pentanoic acid	PFPeA	2706-90-3
Perfluoro-n-butanoic acid	PFBA	375-22-4
Perfluoroalkylsulfonates (PFAS)		
Perfluoro-1-decanesulfonic acid	PFDS	335-77-3
Perfluoro-1-nonanesulfonic acid	PFNS	68259-12-1
Perfluorooctanesulfonic acid	PFOS	1763-23-1
Perfluoro-1-heptanesulfonic acid	PFHpS	375-92-8
Perfluorohexanesulfonic acid	PFHxS	355-46-4
Perfluoro-1-pentanesulfonic acid	PFPeS	2706-91-4
Perfluoro-1-butanesulfonic acid	PFBS	375-73-5
Perfluorooctanesulfonamides (PFOSA)		
Perfluoro-1-octanesulfonamide	FOSA-1	754-91-6
Telomer Sulfonates		
Sodium 1H,1H,2H,2H-perfluorodecane sulfonate (8:2)	8:2FTS	39108-34-4
Sodium 1H,1H,2H,2H-perfluorooctane sulfonate (6:2)	6:2FTS	27619-97-2

Sodium 1H,1H,2H,2H-perfluorohexane sulfonate (4:2)	4:2FTS	757124-72-4
Fluorotelomer carboxylic acids (FTCA)		
2-Perfluorodecyl ethanoic acid	10:2FTCA	53826-13-4
2-Perfluorooctyl ethanoic acid	8:2FTCA	27854-31-5
2-Perfluorohexyl ethanoic acid	6:2FTCA	53826-12-3
Perfluorooctanesulfonamidoacetic Acids		
N-ethylperfluoro-1-octanesulfonamidoacetic acid	N-EtFOSAA	2991-50-6
N-methylperfluoro-1-octanesulfonamidoacetic acid	N-MeFOSAA	2355-31-9
Perfluoro ether carboxylic acids		
Hexafluoropropylene oxide dimer acid	GenX	13252-13-6

3. CURRENT SORBENT TECHNOLOGIES

Sorbent materials have been investigated for treating PFAS contamination for over a decade. The most studied is activated carbon, which is a form of carbon processed to contain very high surface area. Activated carbon is often made from charcoal or coal, and is currently the standard sorbent used for most *ex situ* (i.e. treatment is performed outside the groundwater system, such as systems that pump water out, through vessels containing sorbent, and then pump back treated water into the groundwater system) treatment efforts to mitigate PFAS contamination in groundwater, primarily due to its wide availability and relatively low cost (Merino et al. 2016, Kucharzyk et al. 2017, Ross et al. 2018, Banks et al. 2020). However, anion exchange resins, which made of porous organic polymers typically as microbeads, can be regenerated (cleaned and reused) more easily than activated carbon (Deng et al. 2015, Woodard et al. 2017, Ross et al. 2018, Banks et al. 2020); biochars are similar to activated carbon in principle, but offer a cost-effective alternative to activated carbon, as they are typically made from pyrolysis of waste organic material (Chen et al. 2011, Ahmad et al. 2014, Xiao et al. 2017). The main difference between biochar and activated carbon, as differentiated here, is that biochar is created from waste materials and can therefore have more variability in properties compared with activated carbon, which is created under more tightly controlled conditions. Further, due to being created from water materials, biochars are attractive due to lower cost to produce and reuse of water materials. Each of these sorbents are described in detail below. In addition, some promising novel sorbents are discussed. Finally, a discussion on current treatment train technologies (using more than one sorbent) is provided.

3.1 ACTIVATED CARBON

The effectiveness of activated carbon for removing PFAS from solution (primarily PFOS and PFOA, but other PFAAs to a lesser extent) has been relatively widely studied. Table A-1 summarizes a selection of studies that tested the efficacy of three forms of activated carbon for removal of PFAS from groundwater: granulated activated carbon (GAC), particulate activated carbon (PAC) and colloidal activated carbon (CAC).

3.1.1 GAC

Of the main forms of activated carbon, GAC has been the most commonly used; most studies found that Filtrasorb 400, made by Calgon Carbon Company, is the most efficient at removing PFAS, compared to other commercially available GAC types (Ochoa-Herrera and Sierra-Alvarez 2008, McCleaf et al. 2017, Liu et al. 2019, Siriwardena et al. 2019). Filtrasorb 300 by Calgon Carbon Company has been used frequently as well and is also seemingly effective (Appleman et al. 2013, 2014, Dickenson and Higgins 2016, Xiao et al. 2017), although a study by Ochoa-Herrera and Sierra Alvarez (2008) found that Filtrasorb 400 had a higher capacity for PFOS than Filtrasorb 300. Tests using GAC developed from different materials, which results in different properties, have had mixed success. For example, GAC derived from bamboo, developed and tested by Deng et al. (2015), was found to be more effective than coal-based GAC in that study, whereas another study found that coconut-derived GAC was less effective at removing PFAS than coal-based GAC (Siriwardena et al. 2019). These differences in efficacy of PFAS removal appear to be driven by varying adsorbent properties between types of GAC, such as the size of and number of micropores, surface area, and possible increased micelle/hemi-micelle formation of PFAS within the amendment material, which can increase sorbent efficacy at removing PFAS from water (Yu et al. 2009, Siriwardena et al. 2019).

3.1.2 PAC

While PAC has been shown to be effective at removing PFAS, and in some studies was more effective than GAC (Yu et al. 2009, 2012, Pramanik et al. 2015), it is typically not reactivated/reused (thereby increasing waste and total cost of this treatment), and generally requires a filtration step to remove the very small sorbent particulates from groundwater after treatment, making it less ideal than GAC in P&T systems (Ross et al. 2018).

3.1.3 CAC

CAC is relatively new and is designed specifically for injection into a groundwater system for *in situ* remediation. McGregor (2018) found that PFAA were reduced below detection level at one site in Canada 18 months after injection of CAC into the groundwater system. Currently, CAC has not been tested alongside GAC or PAC to determine its relative effectiveness, although Carey et al. (2019) performed a batch experiment (Table A-1), that suggests CAC is similarly less effective at removing short-chain vs. long-chain PFAA, as in other activated carbon sorbents.

3.1.4 Concentration and Compound-Specific Results

Activated carbons have been demonstrated to reduce PFOS by 90% at parts per billion or parts per million concentrations (e.g. Ochoa-Herrera and Sierra-Alvarez 2008; Eschauzier et al. 2012), however, this efficiency seems to be reduced when PFAS fall into the part per trillion (ppt) levels (McCleaf et al. 2017, Liu et al. 2019). This suggests that reducing PFAS to below suggested health thresholds (i.e. 70 ppt for PFOS and PFOA) could be very challenging using activated carbon alone.

GAC has also been shown to be less effective at removing PFOA and many of the short-chained PFAA compared to PFOS, resulting in reduced sorption efficiency and faster breakthrough for those compounds (Ochoa-Herrera and Sierra-Alvarez 2008, Xiao et al. 2017, McCleaf et al. 2017, Ross et al. 2018, Liu et al. 2019). Further, several studies have noted that PFSA tend to adsorb better than PFCA with activated carbon treatments (Ochoa-Herrera and Sierra-Alvarez 2008, Kothawala et al. 2017, McCleaf et al. 2017), and several studies have noted apparent desorption of short-chain PFAA (e.g. PFBS, PFHxS) during treatment, suggesting that long-chained PFAA and possibly NOM outcompete the short-chain PFAA (Eschauzier et al. 2012, McCleaf et al. 2017). As these compounds desorb, the amendment could effectively become a secondary source zone for short-chain PFAA (Ross et al. 2018).

In more recent studies that used more environmentally relevant conditions for activated carbon tests (e.g. mixtures of PFAS constituents, initial concentrations of PFAS in the parts per trillion range, presence of competing ions, and natural organic material [NOM]), compared to earlier, more simplistic tests that typically used high concentrations of a single PFAS constituent in otherwise clean laboratory water, the efficiency of activated carbon at removing PFAS was decreased significantly; these results demonstrate the need for testing sorbents in environmentally realistic conditions (Ross et al. 2018, Ateia et al. 2019a).

Overall, activated carbon appears to be relatively effective at remediating PFOA and PFOS, which are currently the two PFAA under the most regulatory scrutiny, but there is a growing consensus that activated carbon sorbents are not as useful for mitigating contamination by other PFAA that are becoming increasingly scrutinized.

3.1.5 Water Quality

As alluded to above, other water quality parameters may alter the efficacy of activated carbon at removing PFAS, as these change the chemistry of both the sorbate (PFAS) and the sorbent (Banks et al. 2020); however, more study is needed. In general, as pH increases, the rate of sorption and overall capacity of GAC and PAC seem to decrease for PFOA and PFOS (Yu et al. 2009, Deng et al. 2015, Wu et al. 2020). Yu et al. (2009) posited this was due to the electrostatic interactions between the positively-charged activated carbon surface (i.e. pH of zero charge = 7.5), which is enhanced in low pH solutions (3) rather than higher pH solutions (7). In essence, when the pH of zero charge (e.g. the solution pH that would result in the surface of the sorbent to be neither negatively nor positively charged), is higher than the pH of the solution, the sorbent surface is positively charged and the electrostatic interactions between the anion PFAAs and the sorbent surface will be favorable. In another example, Deng et al. (2015) found that above pH 4, using the bamboo-derived GAC (pH of zero charge = 3.2), the sorption of PFOS and PFOA decreased (stronger effect for PFOA), presumably because the activated carbon became negatively charged on its surface at pH 4 and higher, resulting in electrostatic repulsion of the anionic PFAA.

The effect of NOM on the sorption of PFAA on activated carbons seems to be variable, perhaps depending on the specific NOM and activated carbon characteristics (Yu et al. 2012, Pramanik et al. 2015, Kothawala et al. 2017, McCleaf et al. 2017). Pramanik et al. (2015) found that increasing DOC concentrations led to reduced performance of GAC and PAC in PFOS and PFAS removal, with a larger effect on PAC efficacy. Yu et al. (2012) tested the sorption of PFOA and PFOS on PAC with or without organic matter and found that low molecular weight NOM compounds (<1 kDa) directly compete for binding sites with PFAA, and larger NOM compounds (>30 kDa) restrict binding due to pore blockage. In contrast some studies have found enhanced sorption with higher dissolved organic matter (DOM) concentrations in reservoir water (Kothawala et al. 2017, McCleaf et al. 2017).

3.2 ION-EXCHANGE RESINS

Ion-exchange resins consist of a polymer structured with a charged functional group balanced by a counter ion in a polystyrene or polyacrylic matrix. While these resins are typically more expensive than activated carbon, they can be regenerated (i.e. contaminants removed for reuse), have quicker sorption times, and potential for higher total contaminant capacities, making them appealing (Dickenson and Higgins 2016, Merino et al. 2016, Ross et al. 2018). Table A-2 summarizes selected studies that tested the efficacy of ion-exchange resins to remove PFAS. Ion exchange studies have primarily focused on the removal of anionic PFAA using anionic exchange resins (AIX). The properties of (AIX) generally differ from one another in three ways: polymer matrix, porosity, and charged functional group. In a study of the sorption of PFOS with six different AIX, Deng et al. (2010) found that the matrix was the most important factor, with polyacrylic matrices resulting in faster sorption and higher capacities of PFOS than polystyrene. Further, macroporous AIX resulted in faster sorption for both matrices and higher capacity for polystyrene only (Deng et al. 2010).

Similar to activated carbon, AIX seem to be more effective at removing long chained PFAA and less effective at removing short chained PFAA, and more effective in general with PFSA than PFCA, when comparing compounds of similar length (Chen et al. 2011, Dickenson and Higgins 2016, Ross et al. 2018, Ateia et al. 2019a). Further, Zaggia et al. (2016) found, in a phenomenon similar to what has been observed with activated carbons, that short-chained PFAA appear to desorb as they are outcompeted for binding sites by long-chained PFAA over time. Several studies have compared AIX and GAC and have generally found that AIX generally performs better than GAC, resulting in more sorption of PFAA, on a by-weight basis (Kothawala et al. 2017, McCleaf et al. 2017), by-volume basis (Franke et al. 2019), or following specifications from the manufacturer (Woodard et al. 2017). While AIX may be an improvement over GAC for PFAS remediation, other data are required to understand their effectiveness in more environmentally relevant conditions (low concentrations of PFAS, PFAS mixtures, presence of NOM and background ions, etc.).

3.2.1 Water quality

The effects of water quality parameters, similar to their impacts to the efficacy of activated carbon treatments, can modify the effectiveness of AIX on PFAA sorption and these impacts are greatly dependent on the AIX properties. The effect of pH is dependent on the functional group responsible for ion exchange. For example, IRA67 (with a polyamine functional group) had a significant reduction in sorption for PFOS above a pH of 10 whereas IRA958 (with a quaternary ammonium functional group) saw no effect, presumably because the former's functional group converted to its base form and lost the ability to anion exchange (Deng et al. 2010). Another study found a significant reduction in removal efficiency of Purolite A860 above pH 6 for PFOA and above pH 7 for PFOS (Dixit et al. 2019). Looking at the effect of NOM, Dixit et al. (2019) determined that the higher charge density of the NOM, the greater the decrease in PFAS uptake by AIX due to competition effects (high charge density NOM molecules are preferentially removed by the AIX compared to PFAS). Particularly large NOM molecules can also block AIX pores, reducing the efficacy on PFAS remediation (Dixit et al. 2019). Finally, Deng et al. (2010) found that inorganic ions of sulfate (concentrations up to 1.04 mmol/L) and chromate (VI) (concentrations up to 2.00 mmol/L) caused significant reductions in PFOS sorption, likely due to competition effects. Therefore, when determining the best AIX resin to use for a given site, it is critical to factor in the water quality parameters of the site, and how these may interact with the AIX properties.

3.3 BIOCHARS

Biochar is a carbon-rich material that is synthesized through pyrolysis/carbonization of plant and animal material; historically, biochars were mostly used as an agricultural amendment, but the use of biochar for pollution remediation is an area of increasing research interest (Ahmad et al. 2014). Biochars provide a way to reduce agricultural waste and generally are less expensive to create compared to AIX and GAC, increasing their appeal for the treatment of PFAS (Chen et al. 2011, Ahmad et al. 2014, Kucharzyk et al. 2017, Militao et al. 2021). Similar to both AIX and activated carbon treatments, the efficacy of biochars for remediation of contaminants, including PFAS, is dependent on the material's surface area, pore size distribution, and ion-exchange capacity (Chen et al. 2011, Ahmad et al. 2014, Kucharzyk et al. 2017, Militao et al. 2021). Chen et al. (2011) tested three different biochars: a maize straw and willow derived char as well as a maize-straw origin ash. They found that the maize-straw origin ash resulted in faster sorption and higher PFOS capacity than GAC and was similarly effective compared to PAC, whereas the other two biochars were much less effective (Chen et al. 2011). The authors hypothesized that surface area differences drove these observations; the surface area of the maize-straw origin ash was much higher than either of the other two biochars by a factor of 3; in addition, the ash had a positively charged surface, resulting in electrostatic interactions that likely accelerated sorption (Chen et al. 2011). Xiao et al. (2017) found a similar result; a high surface-area biochar (Mountain Crest Gardens, Gropro, INC) removed PFAS with similar efficacy compared with GAC (F300, Calgon Carbon Company), whereas low surface area biochars underperformed. So far, biochars have not been as well tested as GAC or AIX in terms of understanding how differences in water quality (pH, NOM, background ions) affect sorption, or how biochar performs for sorption of short-chained compared to long-chain PFAS. A recent study by Vo et al. (2022) studied the effect of pH, ion concentration, and NOM on the sorption of a biochar and found that while pH and ion concentration did not appear to have a major effect, NOM enhanced the sorption of PFAAs. This is a data gap that needs to be addressed, to consider the use of biochars for PFAS remediation

3.4 NOVEL SORBENTS

There has been considerable effort, especially through DoD programs such as the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP), to develop novel sorbents that are PFAS selective (thereby limiting effects on sorbent efficacy due to the presence of NOM and competing ions) and are more effective at removing short chained PFAS (e.g. PFBS) than existing sorbents. Many of these novel sorbents are still in the development stage and are not commercially available, and thus not feasible to evaluate for this study. These are therefore not discussed at length here. The novel sorbent literature has been reviewed recently by several authors (Horst et al. 2018, Ross et al. 2018, Ateia et al. 2019a). Two novel sorbents that look promising for removal of short-chained PFAS are: (1) a reduced form of a β-cyclodextrin polymer linked with tetrafluoroterephthalonitrile (reduced TFN-CDP) and (2) N-[3-(dimethylamino)propyl] acrylamide, methyl chloride quaternary hydrogel (DMAPAA-Q). Both of these novel polymers feature faster kinetics and higher sorption capacities for short-chained PFAS compared to AIX and GAC, at environmentally relevant concentrations (in the µg/l to ng/L range); for example, reduced TFN-CDP removed 80% of PFBS after 30 minutes of contact time and DMAPAA-Q had equilibration time of 60-120 mins for various PFAS (Ateia et al. 2019b, Klemes et al. 2019). While promising, these sorbents are not as mature as activated carbons, AIX resins, and biochars, and may not be available for evaluation under this project.

3.4.1 Osorb ©

One novel sorbent that is nearly commercially available is swellable organically modified silica (commercially called Osorb©) that could be effective for PFAS remediation (Horst et al. 2018, Ross et al. 2018, Stebel et al. 2019). This compound physically swells in the presence of organic chemicals, which opens mesopores and allows binding of longer-chained PFAS. A recent study modified the Obsorb© matrix by 1) incorporating a fluoroalkyl group, 2) incorporating a quaternary amine group, and 3) entrapping a cationic imidazolium containing polymer within the swellable organically modified silica (Stebel et al. 2019). That study found that while both the unmodified Osorb© matrix and the modified matrix that incorporated a fluoroalkyl group (modification 1) adsorbed long-chain PFAS solutes, especially under high ionic strength conditions (50 mM NaCl), this did not extend to shorter-chained PFAS (Stebel et al. 2019). The second modified matrix that incorporated a quaternary amine group caused the Obsorb© material to become a fine powder, which resulted in very fast sorption; however it was unclear if this was due to the modified structure or simply because the material was powdered. That study notes that unswelled Osorb© sorbed short chained PFAS but not long chained PFAS, and that the opposite was true for the matrix after it had swelled. Finally, the third tested modification, with Osorb© matrix incorporating a cationic imidazolium polymer, was able to adsorb the full spectrum of tested PFAA, presumably due to the anion interactions with the cations of the polymer when the hydrophobic interactions were not strong enough to sorb the short chained PFAA (Stebel et al. 2019). The effect of water quality characteristics, such as background ions, pH, and NOM content for this sorbent, is still untested.

3.5 TREATMENT TRAINS INVOLVING SORBENTS

Due to the diversity of chemical properties of different PFAS compounds, there is a growing consensus that using multiple treatment strategies (“treatment trains”), either in tandem or in parallel, will be required for PFAS remediation (Simon et al. 2019). Currently, the DoD is investing heavily in treatment train technologies (e.g. SERDP projects ER18-1278, ER18-1306). Treatment trains that in general have shown success are tandem processes that involved using a sorbent, and then an *in situ* degradative technology, such as zero-valent iron, activated persulfate, or thermal mineralization to remove PFAS using a P&T system (Lu et al. 2020).

This NESDI study is focused on the use of multiple separation/sorption technologies to remediate PFAS contamination, rather than incorporating degradative technologies. This approach intends to use multiple separation technologies (e.g. sorbents, filtration) that remove both short and long chained PFAS under natural water quality conditions to obtain higher efficiencies in PFAS sorption and removal. One application for this strategy is adding sorbents to existing water treatment plant technologies, as the majority of conventional water remediation technologies are not effective against PFAS (Eschauzier et al. 2012, Appleman et al. 2013, 2014, Du et al. 2014, Dickenson and Higgins 2016), or *in situ* treatment at a site. In general, treatment train studies have used GAC primarily with AIX resins as an additional sorbent step, and these were generally successful at removing long-chained PFAA, but less so with short-chained PFAS. Another strategy involved using RO filtration to provide clean water, and then using GAC and AIX to adsorb PFAS from the reject water (in which PFAS were concentrated) (Franke et al. 2019). Franke et al. (2019) found that the mass of PFAS adsorbed to the GAC and AIX was 2.6 and 4.1 times higher, respectively, when used to filter the concentrate rather than the raw waste water. Using multiple types of sorbents in sequence has also been suggested (Ross et al. 2018, Stebel et al. 2019), but does not appear to have been reported in the scientific literature. Ideally, sorbents used in this way would complement each other, such as using GAC to remove most PFAS with an AIX effective against short-chain PFAA as a polishing step.

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4. CONSIDERATIONS FOR NESDI PROJECT #578

The results from this literature review indicate that there is a continuing need to assess sorbents for efficacy under a range of conditions including varying water quality, to determine effective sorbents for future *in situ* amendment efforts. This is especially the case for short-chained PFAA that are not currently part of regulatory frameworks, but are expected to be regulated in the near future. Major data gaps exist in comparing adsorbents to each other under the same experimental conditions. Some studies have compared AIX and GAC to each other (Senevirathna et al. 2010, Appleman et al. 2014, Dickenson and Higgins 2016, Kothawala et al. 2017, Franke et al. 2019), but generally with only one commercial product of each type of sorbent and without modifying water quality conditions to see if relative performance changes. Based on the review presented here, and the conclusions from literature reviews of sorbents (i.e. Ross et al. 2018, Ateia et al. 2019a), it seems prudent for this NESDI project to test high surface area GAC, biochars, and strongly-basic AIX resins in a range of relevant water quality conditions using environmentally-realistic concentrations of PFAS (in the ng/L to µg/L range). This is critical as adsorbents seem more efficient at removal of PFAS at higher concentrations, and because even with over 90% removal of PFAS, for sites with contamination in the mg/L concentration range, this would not result in remediating PFAS below the health advisory guidelines in the US (5-70 ng/L for PFOS/PFOA). In addition, a direct comparison of CAC performance to GAC and other adsorbents would be ideal for use in future *in situ* groundwater remediation decisions. Finally, swellable organically modified silica seems like a possibly effective adsorbent, but more rigorous, comparable testing is needed, which can be provided with the planned lab and field studies for this project.

4.1 OVERVIEW OF NAVY GROUNDWATER WATER QUALITY PARAMETERS

Table 2 provides summary data for ancillary measurements of groundwater quality parameters analyzed from several Navy sites with PFAS contamination. These data were collated from available data from the PFAS reading library. Of note is that the pH at these sites tend to be higher than many of the lab studies published so far (in the 6-8 range). Most studies used lower pH solutions, as most of these sorbents work better in more acidic environments, especially when there is a reliance on electrostatic interactions, such as with anion exchange resins, because sorbent surfaces lose positive charges as pH increases. Also noteable is that some sites, such as Tustin MCAS, have relatively high specific conductivity (e.g. 43.90 mS/cm), which suggests high levels of background ions that could compete with PFAS for sorption sites. This NESDI study will use more-realistic laboratory conditions, as well as onsite testing, to provide needed data on the efficacy of various sorbents at remediating PFAS from groundwater at Navy sites.

Table 2. Summary of average water quality parameters for groundwater with PFAS contamination concerns at several Navy sites.

Site	Date sampled	Temp (C˚)	pH	Sp Cond (mS/cm)	Turbidity (NTU)	Dissolved Oxygen (mg/L)	Salinity (ppt)	Reference
Tustin MCAS (BRAC)	July-17	21.88	7.76	43.90	25.90	N/A	N/A	1
	November-17	18.08	6.78	7.88	10.97	N/A	N/A	2
Bedford NWIRP (Active)	September-19	18.47	6.32	0.57	3.44	N/A	N/A	3
New London NSB Site 2A (Active)	November-18	14.25	6.54	2.47	7.06	N/A	N/A	4
New London NSB Site 8 (Active)	November-18	16.74	9.10	2.96	33.27	N/A	N/A	4
Point Mugu NBVC Site 24 (Active)	October-17	24.52	7.03	8.29	15.74	1.52	N/A	5
Twentynine Palms CA MAGCC Site 10 (Active)	November-17,-18	21.95	8.43	21.58	42.61	5.14	N/A	6
CID Corry Station (Active)	March-19	22.48	5.15	0.10	2.76	0.48	0.05	7
NAS Whidbey Island, Ault Field	January-17	12.42	7.15	0.92	3.80	4.23	N/A	8

[1]MMEC 2017, [2]MMEC 2018, [3]RSJV 2019, [4]IEI 2018, [5]SOJV 2017, [6]BRADY GCE II 2019, [7]Resolution Consultants 2019, [8]Sealaska Environmental Services, LLC 2017.

5. REFERENCES

Ahmad, M., A. U. Rajapaksha, J. E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S. S. Lee, and Y. S. Ok. 2014. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere 99:19–33.

Ahrens, L., and M. Bundschuh. 2014. Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: A review. Environmental Toxicology and Chemistry 33:1921–1929.

Appleman, T. D., E. R. V. Dickenson, C. Bellona, and C. P. Higgins. 2013. Nanofiltration and granular activated carbon treatment of perfluoroalkyl acids. Journal of Hazardous Materials 260:740–746.

Appleman, T. D., C. P. Higgins, O. Quiñones, B. J. Vanderford, C. Kolstad, J. C. Zeigler-Holady, and E. R. V. Dickenson. 2014. Treatment of poly- and perfluoroalkyl substances in U.S. full-scale water treatment systems. Water Research 51:246–255.

Ateia, M., A. Alsbaiee, T. Karanfil, and W. Dichtel. 2019a. Efficient PFAS Removal by Amine-Functionalized Sorbents: Critical Review of the Current Literature. Environmental Science & Technology Letters 6:688–695.

Ateia, M., M. Arifuzzaman, S. Pellizzeri, M. F. Attia, N. Tharayil, J. N. Anker, and T. Karanfil. 2019b. Cationic polymer for selective removal of GenX and short-chain PFAS from surface waters and wastewaters at ng/L levels. Water Research 163.

Banks, D., B.-M. Jun, J. Heo, N. Her, C. M. Park, and Y. Yoon. 2020. Selected advanced water treatment technologies for perfluoroalkyl and polyfluoroalkyl substances: A review. Separation and Purification Technology 231.

Barzen-Hanson, K. A., S. C. Roberts, S. Choyke, K. Oetjen, A. McAlees, N. Riddell, R. McCrindle, P. L. Ferguson, C. P. Higgins, and J. A. Field. 2017. Discovery of 40 Classes of Per- and Polyfluoroalkyl Substances in Historical Aqueous Film-Forming Foams (AFFFs) and AFFF-Impacted Groundwater. Environmental Science and Technology 51:2047–2057.

Birnaum, L. 2018. Testimony before the Senate Committee on Homeland Security and Governmental Affairs Subcommittee on Federal Spending Oversight and Emergency Management. National Insittute of Environmental Health Sciences 3.

Buck, R. C., J. Franklin, U. Berger, J. M. Conder, I. T. Cousins, P. De Voogt, A. A. Jensen, K. Kannan, S. A. Mabury, and S. P. J. van Leeuwen. 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. Integrated Environmental Assessment and Management 7:513–541.

California Water Boards (CWB). 2019. State Water Board updates guidelines for testing and reporting PFOA and PFOS as it assess scope of problem. Press release. August, 23, 2019. https://www.waterboards.ca.gov/press_room/press_releases/2019/pr082319_pfoa_pfos_guidelines_news_release.pdf

Chen, X., X. Xia, X. Wang, J. Qiao, and H. Chen. 2011. A comparative study on sorption of perfluorooctane sulfonate (PFOS) by chars, ash and carbon nanotubes. Chemosphere 83:1313–1319.

Conder, J. M., J. Arblaster, E. Larson, J. Brown, and C. P. Higgins. 2019. Guidance for Assessing the Ecological Risks of PFASs to Threatened and Endangered Species at Aqueous Film Forming Foam-Impacted Sites. Page SERDP Project ER18-1614. Huntingon Beach, CA.

Conder, J. M., R. A. Hoke, W. De Wolf, M. H. Russell, and R. C. Buck. 2008. Are PFCAs bioaccumulative? A critical review and comparison with regulatory criteria and persistent lipophilic compounds. Environmental Science and Technology 42:995–1003.

Deng, S., Y. Nie, Z. Du, Q. Huang, P. Meng, B. Wang, J. Huang, and G. Yu. 2015. Enhanced adsorption of perfluorooctane sulfonate and perfluorooctanoate by bamboo-derived granular activated carbon. Journal of Hazardous Materials 282.

Deng, S., Q. Yu, J. Huang, and G. Yu. 2010. Removal of perfluorooctane sulfonate from wastewater by anion exchange resins: Effects of resin properties and solution chemistry. Water Research 44:5188–5195.

Department of the Navy, Naval Facilities Engineering Command Northwest 2017. Annual 2016-2017 Groundwater Long-Term Monitoring Report for Operable Unit 1 Area 6 and Operable Unit 5 Area 31, NAS Whidbey Island, Oak Harbor, Washington. August.

Dickenson, E. R., and C. Higgins. 2016. Treatment Mitigation Strategies for Poly- and Perfluoroalkyl Substances.

Dixit, F., B. Barbeau, S. G. Mostafavi, and M. Mohseni. 2019. PFOA and PFOS removal by ion exchange for water reuse and drinking applications: Role of organic matter characteristics. Environmental Science: Water Research and Technology 5:1782–1795.

Du, Z., S. Deng, Y. Bei, Q. Huang, B. Wang, J. Huang, and G. Yu. 2014. Adsorption behavior and mechanism of perfluorinated compounds on various adsorbents-A review. Journal of Hazardous Materials 274:443–454.

Eschauzier, C., E. Beerendonk, P. Scholte-Veenendaal, and P. De Voogt. 2012. Impact of Treatment Processes on the Removal of Perfluoroalkyl Acids from the Drinking Water Production Chain. Environmental Science & Technology 46:1708–1715.

Franke, V., P. McCleaf, K. Lindegren, and L. Ahrens. 2019. Efficient removal of per- And polyfluoroalkyl substances (PFASs) in drinking water treatment: Nanofiltration combined with active carbon or anion exchange. Environmental Science: Water Research and Technology 5:1836–1843.

Horst, J., J. McDonough, I. Ross, M. Dickson, J. Miles, J. Hurst, and P. Storch. 2018. Water Treatment Technologies for PFAS: The Next Generation. Groundwater Monitoring and Remediation 38:13–23.

Klemes, M. J., Y. Ling, C. Ching, C. Wu, L. Xiao, D. E. Helbling, and W. R. Dichtel. 2019. Reduction of a Tetrafluoroterephthalonitrile-β-Cyclodextrin Polymer to Remove Anionic Micropollutants and Perfluorinated Alkyl Substances from Water. Angewandte Chemie International Edition 58:12049–12053.

Kothawala, D. N., S. J. Köhler, A. Östlund, K. Wiberg, and L. Ahrens. 2017. Influence of dissolved organic matter concentration and composition on the removal efficiency of perfluoroalkyl substances (PFASs) during drinking water treatment. Water Research 121.

Kucharzyk, K. H., R. Darlington, M. Benotti, R. Deeb, and E. Hawley. 2017. Novel treatment technologies for PFAS compounds: A critical review. Journal of Environmental Management 204.

Liu, C. J., D. Werner, and C. Bellona. 2019. Removal of per- And polyfluoroalkyl substances (PFASs) from contaminated groundwater using granular activated carbon: A pilot-scale study with breakthrough modeling. Environmental Science: Water Research and Technology 5.

Lu, D., S. Sha, J. Luo, Z. Huang, and X. Zhang Jackie. 2020. Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): A critical review. Journal of Hazardous Materials 386:121963.

McCleaf, P., S. Englund, A. Östlund, K. Lindegren, K. Wiberg, and L. Ahrens. 2017. Removal efficiency of multiple poly- and perfluoroalkyl substances (PFASs) in drinking water using granular activated carbon (GAC) and anion exchange (AE) column tests. Water Research 120:77–87.

Merino, N., Y. Qu, R. A. Deeb, E. L. Hawley, M. R. Hoffmann, and S. Mahendra. 2016. Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl Substances in Water. Environmental Engineering Science 33:615–649.

Militao, I. M., F. A. Roddick, R. Bergamasco, L. Fan. 2021. Removing PFAS from aquatic systems using natual and renewable material-based adsorbents: A review. Journal of Environmental Chemical Engineering 9 (2021): 105271

Multimedia Environmental Compliance Group (MMEC). 2016. Final CERCLA Five-year review report, Operable Units 1A, 1B North, 1B South, 3, and 4B, Former Marine Corps Air Station Tustin, Tustin, California. October.

Multimedia Environmental Compliance Group (MMEC) 2017. Final sampling and analysis plan for per- and polyfluoroalkyl sampling for groundwater remedial action at Operable Unit 3, Installation Restoration Program Site 1,Former Marine Corps Air Station Tustin, Tustin, California. July.

Naval Facilities Engineering Command Southwest 2018. Final groundwater monitoring report, Second semiannual period of 2017, Installation restoration program site 24, Naval base ventura county, Point Mugu, CA. July.

Naval Facilities Engineering Command Southwest 2019. Final semi-annual groundwater monitoring report, Underground storage tank site 10, Marine corps air ground combat center, Twentynine Palms, Ca. August.

Ochoa-Herrera, V., and R. Sierra-Alvarez. 2008. Removal of perfluorinated surfactants by sorption onto granular activated carbon, zeolite and sludge. Chemosphere 72:1588–1593.

Pramanik, B. K., S. K. Pramanik, and F. Suja. 2015. A comparative study of coagulation, granular- and powdered-activated carbon for the removal of perfluorooctane sulfonate and perfluorooctanoate in drinking water treatment. Environmental Technology (United Kingdom) 36:2610–2617.

Renova-Sovereign Joint Venture (RSJV) 2019. September 2019 Semi Annual Goundwater Monitoring Report Southern Flight Test Area NWIRP Bedford M, Naval Weapons Industrial Reserve Plant, Bedford, Massachusetts. December.

Ross, I., J. McDonough, J. Miles, P. Storch, P. Thelakkat Kochunarayanan, E. Kalve, J. Hurst, S. S. Dasgupta, and J. Burdick. 2018. A review of emerging technologies for remediation of PFASs. Remediation 28:101–126.

Senevirathna, S. T. M. L. D., S. Tanaka, S. Fujii, C. Kunacheva, H. Harada, B. R. Shivakoti, and R. Okamoto. 2010. A comparative study of adsorption of perfluorooctane sulfonate (PFOS) onto granular activated carbon, ion-exchange polymers and non-ion-exchange polymers. Chemosphere 80:647–651.

Simon, J. A., S. Abrams, T. Bradburne, D. Bryant, M. Burns, D. Cassidy, J. Cherry, S. Y. Chiang, D.

Cox, M. Crimi, E. Denly, B. DiGuiseppi, J. Fenstermacher, S. Fiorenza, J. Guarnaccia, N. Hagelin, L. Hall, J. Hesemann, E. Houtz, S. S. Koenigsberg, F. Lauzon, J. Longsworth, T. Maher, A. McGrath, R. Naidu, C. J. Newell, B. L. Parker, T. Singh, P. Tomiczek, and R. Wice. 2019. PFAS Experts Symposium: Statements on regulatory policy, chemistry and analtyics, toxicology, transport/fate, and remediation for per- and polyfluoroalkyl substances (PFAS) contamination issues. Remediation 29:31–48.

Siriwardena, D. P., M. Crimi, T. M. Holsen, C. Bellona, C. Divine, and E. Dickenson. 2019. Influence of groundwater conditions and co-contaminants on sorption of perfluoroalkyl compounds on granular activated carbon. Remediation 29:5–15.

Stebel, E. K., K. A. Pike, H. Nguyen, H. A. Hartmann, M. J. Klonowski, M. G. Lawrence, R. M. Collins, C. E. Hefner, and P. L. Edmiston. 2019. Absorption of short-chain to long-chain perfluoroalkyl substances using swellable organically modified silica. Environmental Science: Water Research and Technology 5:1854–1866.

Vo, H.N.P., T.M.H. Nguyen, H.H. Ngo, W. Guo, P. Shukla. 2022. Biochar sorption of perfluoroalkyl substances (PFASs) in aqueous film-forming foams-impacted groundwater: Effects of PFASs properties and groundwater chemistry. Chemosphere 286(2022): 131622

Wang, Z., J. C. Dewitt, C. P. Higgins, and I. T. Cousins. 2017. A Never-Ending Story of Per- and Polyfluoroalkyl Substances (PFASs)? Environmental Science and Technology 51:2508–2518.

Woodard, S., J. Berry, and B. Newman. 2017. Ion exchange resin for PFAS removal and pilot test comparison to GAC. Remediation 27.

Xiao, X., B. A. Ulrich, B. Chen, and C. P. Higgins. 2017. Sorption of Poly- and Perfluoroalkyl Substances (PFASs) Relevant to Aqueous Film-Forming Foam (AFFF)-Impacted Groundwater by Biochars and Activated Carbon. Environmental Science and Technology 51:6342–6351.

Yu, J., L. Lv, P. Lan, S. Zhang, B. Pan, and W. Zhang. 2012. Effect of effluent organic matter on the adsorption of perfluorinated compounds onto activated carbon. Journal of Hazardous Materials 225–226:99–106.

Yu, Q., R. Zhang, S. Deng, J. Huang, and G. Yu. 2009. Sorption of perfluorooctane sulfonate and perfluorooctanoate on activated carbons and resin: Kinetic and isotherm study. Water Research 43:1150–1158.

Wu, C., M. J. Klemes, B. Trang, W.R. Dichtel, Damian E. Helbling. 2020. Exploring the factors that influence the adsoprtion of anionic PFAS on conventional and emerging adsorbents in aquatic matrices. Water Research 182(2020): 115950

Zaggia, A., L. Conte, L. Falletti, M. Fant, and A. Chiorboli. 2016. Use of strong anion exchange resins for the removal of perfluoroalkylated substances from contaminated drinking water in batch and continuous pilot plants. Water Research 91:137–146.

APPENDIX A

Table A-1. Activated Carbon Research Summary Results.

- Effective size indicates the size of pores reported by the manufacturer. Shorthand indicators in table are as follows: SA: surface area of the sorbent reported by the study, SA_{BET}: surface area determined using the Brunauer–Emmett–Teller (BET) method, BVs: equivalent bedvolumes of water treated during testing, GW: groundwater, DI: deionized water, NR: metric not reported, NA: analysis not reported. TOC: total organic carbon, DOC: dissolved organic carbon.

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFBA	GAC	Filtrasorb 300, Calgon	$0.38\ cm^3$	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 10% breakthrough after: 72,000 BVs Creek 100% breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon			Coal	1-µm filtered creek water						Creek: 1248**		Creek 100% breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek 100% breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	100 g	0.071-0111	Coal Effective size: 0.55-0.75 mm SA: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208**	NA,NA	10% column breakthrough at 1422 BVs Ave. removal efficiency 14%	McCleaf et al. 2017
PFPeA	GAC	Filtrasorb 300, Calgon	$0.38\ cm^3$	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 10% breakthrough after: 83,000 BVs Creek 100% breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon			Coal	1-µm filtered creek water						Creek: 1248**		Creek 100% breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut	1-µm filtered creek water						Creek: 912**		Creek 100% breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	NR	0.0163±0.0059	Coal Effective size: 0.55-075 mm SA_{BET}: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.30 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA_{BET}: 614 m^2/g									0.25 µg PFAS/g GAC at 5% breakthrough; Initial breakthrough ~10000 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA_{BET}: 963 m^2/g									0.25 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~7500 BVs	
		GCN1240, Norit			Coconut Effective size = 0.55-075 mm SA_{BET} = 1107 m^2/g									0.20 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~7500 BVs	
		Filtrasorb 400, Calgon	100 g	0.042-0086	Coal Effective size: 0.55-0.75 mm SA: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 1766 BVs Ave. removal efficiency 32%	McCleaf et al. 2017

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFHxA	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 5% Breakthrough after: 72,000 BVs Creek 50% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon			Coal	1-µm filtered creek water						Creek: 1248**		Creek 65% Breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek 70% Breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	NR	0.0184±0.0035	Coal Effective size: 0.55-075 mm SA_{BET}: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.50 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA_{BET}: 614 m^2/g									0.25 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~7500 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA_{BET}: 963 m^2/g									0.50 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~12500 BVs	
		GCN1240, Norit	NR	0.0184±0.0035	Coconut Effective size: 0.55-075 mm SA_{BET}: 1107 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.13	Flow Through	0.17***	NA,NA	0.20 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~5000 BVs	Liu et al. 2019
		Filtrasorb 400, Calgon	100 g	0.061-0117	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 3060 BVs Average removal efficiency of 45%	McCleaf et al. 2017
PFHpA	GAC	Filtrasorb 400, Calgon	NR	0.0066±0.0039	Coal Effective size: 0.55-075, SA_{BET}: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.35 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~27500	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA_{BET}: 614 m^2/g									0.30 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~17500 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA_{BET}: 963 m^2/g									0.40 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~22500 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA_{BET}: 1107 m^2/g									0.25 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	
		Filtrasorb 400, Calgon	100 g	0.062-0115	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 4148 BVs Average removal efficiency of 53%	McCleaf et al. 2017

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFOA	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 5% Breakthrough after: ~56,000 BVs (BVs) Creek: 60% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon				1-µm filtered creek water						Creek: 1248**		Creek: 100% Breakthrough after: 11,000 BVs	
		AquaCarb 1240C	0.38 cm^3	1	Coconut	1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	Creek: 912**	NA,NA	Creek: 100% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Made by author	10 mg	20000-250000	Bamboo-derived Effective size: 0.60-0.85 mm	Spiked DI	25	5	NR	NR	Batch	48	Freundlich, pseudo second order	Adsorption capacity 426.5^a 1.34^d	Deng et al. 2015
		Filtrasorb 400, Calgon	NR	0.0216±0.0036	Coal Effective size: 0.55-075 mm SA_{BET}: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.9	Flow Through	0.17***	NA,NA	0.75 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~20000 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA_{BET}: 614 m^2/g									0.40 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA_{BET}: 963 m^2/g									0.75 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA_{BET}: 1107 m^2/g									0.50 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	
		Filtrasorb 400, Calgon	100 g	0.066-0.116	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 5487 BVs Average removal efficiency of 64%	McCleaf et al. 2017
		Filtrasorb 400, Calgon	100 mg	15000-150000	Coal Effective Size: 0.55-0.75 mm Porosity: 0.627	DI Water (100 mL)	30	7.2 (3 mM PO_4^{3-})	NR	NR	Batch	48**	Langmuir, NA	Adsorption capacity 112.1^a 11.8^b	Ochoa-Herrera and Sierra-Alvarez 2008
		NR,NR	795.22 cm^3	0.55	Total pore volume: 0.865 cm^3/g Micropore volume: 0.354 cm^3/g SA_{BET}: 800 m^2/g	Reservoir water	22	7.2	4.5-25	NR	Flow Through	0.17***	NA,NA	Removal: DOC 4.5: 53% DOC 5: 55% DOC 10: 50% DOC 15: 43% DOC 20: 40% DOC 25: 36%	Pramanik et al. 2015
		Filtrasorb 400, Calgon	5-25 mg	1000	Coal SA_{BET}: 924 m^2/g	Spiked DI water Spiked DI water w/1 mg/L PFOS (125 ml)	NR	7.2 (PO_4^{3-})	NR	NR	Batch	168	Langmuir, NA	Adsorption capacity (single/mixed) 34.4/14.0^a 49.3/15.0^b	Siriwardena et al. 2019
		CBC-OLC 12X30, Calgon	5-25 mg	1000	Coconut SA_{BET}: 908 m^2/g More micropores <2 nm than coal	Spiked DI water Spiked DI water w/1 mg/L PFOS (125 ml)	NR	7.2 (PO_4^{3-})	NR	NR	Batch	168	Langmuir, NA	Adsorption capacity (single/mixed) 14.5/9.5^a 13.7/7.87^b	Siriwardena et al. 2019

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFOA (cont.)	GAC	NR, Sinopharm Chemical Reagent Co.	10 mg	2000-250000	SA$_{BET}$: 712 m^2/g	Spiked DI Water (100 ml)	25	Kinetic: 3 or 7 Isotherm: 5	NR	NR	Batch	168**	Langmuir, pseudo-second order	Adsorption capacity 185.0[a] 0.43[d]	Yu et al. 2009
	PAC	NR,NR	795.22 cm^3	0.55	Total pore volume: 0.365 cm^3/g Micropore volume: 0.154 cm^3/g SA$_{BET}$: 880 m^2/g	Reservoir water	22	7.2	4.5-25	NR	Flow Through	0.17***	NA,NA	Removal: DOC 4.5: 68% DOC 5: 68% DOC 10: 53% DOC 15: 42% DOC 20: 35% DOC 25: 29%	Pramanik et al. 2015
		NR, NR	250 mg	20000	Particle size ≥ 100 µm, SA$_{BET}$: 1000 m^2/g	DI Water (100 mL)	25	6.1	NR	NR	Batch	1*	Langmuir, Pseudo-second order	Adsorption capacity 16.5[a]	Qu et al. 2009
		NR, Sinopharm Chemical Reagent Co.	10 mg	2000-250000	SA$_{BET}$: 812 m^2/g	Spiked DI Water (100 ml)	25	Kinetic: 3 or 7 Isotherm: 5	NR	NR	Batch	12**	Freundlich, pseudo-second order	Adsorption capacity 520.1[a] 1.27[d]	Yu et al. 2009
		NR, Sigma-Aldrich	2-20 mg	10-300	Particle size ≤ 40 µm, SA$_{BET}$: 763.8 m^2/g	Spiked DI, Wastewater (1L)	25	7.2 (1 mM PO$_4^{3-}$)	7.3 effluent	NR	Batch	168**	Freundlich, Pseudo-second order	Adsorption capacity DI: 9.934[C] Wastewater: 1.155[c]	Yu et al. 2012
	PAC (in a membrane bioreactor)	NR, Sigma-Aldrich	30-100 mg	200	Particle size ≤ 40 µm, SA$_{BET}$: 763.8 m^2/g	Wastewater	28	6.8-7.5	NR	NR	Flow Through	720**	NA,NA	~67.7-90.6% removed, increased w/ [PAC]	Yu et al. 2014
PFNA	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 5% breakthrough after: >125,000 Creek 30% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon				1-µm filtered creek water						Creek: 1248**		Creek 65% breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek 75% breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	100 g	0.064-0.119	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 6373 BVs Ave. removal efficiency 70%	McCleaf et al. 2017

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFDA	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 5% breakthrough after: >125,000 BVs Creek 25% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon				1-µm filtered creek water						Creek: 1248**		Creek 85% breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek 80% breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	100 g	0.047-0.108	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 7536 BVs Average removal efficiency of 74%	McCleaf et al. 2017
PFUdA	GAC	Filtrasorb 400, Calgon	100 g	0.022-0.101	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 7910 BVs Average removal efficiency of 78%	McCleaf et al. 2017
PFDoA	GAC	Filtrasorb 400, Calgon	100 g	0.009-0.133	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 2373 BVs Average removal efficiency of 78%	McCleaf et al. 2017
PFTeDA	GAC	Filtrasorb 400, Calgon	100 g	0.00046-0.067	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 1703 BVs Average removal efficiency of 80%	McCleaf et al. 2017
PFPrS	GAC	Filtrasorb 400, Calgon	NR	0.0033±0.0011	Coal Effective size: 0.55-075 mm SA_{BET}: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA_{BET}: 614 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	
		GAC400, Norit	NR	0.0033±0.0011	Coal Effective size: 0.55-075 mm SA_{BET}: 963 m^2/g					Ca 116.3 Mg 34.2 Na 105.1 S 72.12				0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA_{BET}: 1107 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~5000 BVs	

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFBS	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 5% Breakthrough after: 83,000 BVs Creek 80% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon				1-µm filtered creek water						Creek: 1248**		Creek 80% Breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek 80% Breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	NR	0.0024±0.0004	Coal Effective size: 0.55-075 mm SA$_{BET}$: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA$_{BET}$: 614 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~10000 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA$_{BET}$: 963 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~12500 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA$_{BET}$: 1107 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~5000 BVs	
		Filtrasorb 400, Calgon	100 g	0.0075-0.144	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 3771 BVs Average removal efficiency of 49%	McCleaf et al. 2017
		Filtrasorb 400, Calgon	100 mg	15000-150000	Coal Effective Size: 0.55-0.75 mm Porosity: 0.627	DI Water (100 mL)	30	7.2 (3 mM PO$_4^{3-}$)	NR	NR	Batch	48**	Langmuir, NA	Adsorption capacity 98.70^a 9.3^b	Ochoa-Herrera and Sierra-Alvarez 2008
PFPeS	GAC	Filtrasorb 400, Calgon	NR	0.0094±0.002	Coal Effective size: 0.55-075 mm SA$_{BET}$: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.25 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA$_{BET}$: 614 m^2/g									0.10 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~12500 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA$_{BET}$: 963 m^2/g									0.25 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA$_{BET}$: 1107 m^2/g									0.10 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs; initial breakthrough ~15000 BVs	

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFHxS	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: Breakthrough after: 83,000 BVs Creek 35% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon				1-µm filtered creek water						Creek: 1248**		Creek 70% Breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek 80% Breakthrough after: 11,000 BVs	
		Filtrasorb 400, Calgon	NR	0.042±0.0076	Coal Effective size: 0.55-075 mm SA$_{BET}$: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	1.60 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~17500 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA$_{BET}$: 614 m^2/g									1.0 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA$_{BET}$: 963 m^2/g									1.50 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~17500 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA$_{BET}$: 1107 m^2/g									0.80 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~7500 BVs	
		Filtrasorb 400, Calgon	100 g	0.071-0.116	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 10214 BVs Average removal efficiency of 69%	McCleaf et al. 2017
PFHpS	GAC	Filtrasorb 400, Calgon	NR	0.0012±0.0003	Coal Effective size: 0.55-075 mm SA$_{BET}$: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~27500 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon			Coal SA$_{BET:}$ 614 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~27500 BVs	
		GAC400, Norit			Coal Effective size 0.55-075 mm SA$_{BET}$: 963 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~27500 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA$_{BET}$: 1107 m^2/g									0.05 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~12500 BVs	

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] µg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFOS	CAC	Plumestop, NR	NR	DI: 0-80 GW: 208	Colloidal Activated Carbon	Spiked DI; Groundwater sample container PFAS mixture	NR	DI: 7.5 GW: 7.4	NR (TOC in GW was 23.8)	NR	Batch	NR	Freundlich, NA	Adsorptive capacity: DI: 142,800^{e} GW: 4900^{e}	Carey et al. 2019
	GAC	Filtrasorb 300, Calgon	0.38 cm^3	1	Coal	Spiked DI, 1-µm filtered creek water	NR	NR	Creek: 1.7	NR	Flow Through	DI: 1032** Creek: 768**	NA,NA	DI: 5% Breakthrough after: >125,000 BVs Creek: 25% Breakthrough after: 11,000 BVs	Appleman et al. 2013
		Filtrasorb 600, Calgon				1-µm filtered creek water						Creek: 1248**		Creek: 65% Breakthrough after: 11,000 BVs	
		AquaCarb 1240C			Coconut							Creek: 912**		Creek: 70% Breakthrough after: 11,000 BVs	
		Made by author	10 mg	20000-250000	Bamboo-derived Effective size: 0.60-0.85 mm	Spiked DI	25	5	NR	NR	Batch	48	Freundlich, pseudo second order	Adsorption capacity 1100.3^{a} 3.20^{d}	Deng et al. 2015
		Filtrasorb 400, Calgon	NR	0.0506±0.0163	Coal Effective size: 0.55-075 mm SA_{BET}: 785 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.10	Flow Through	0.17***	NA,NA	2.5 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~27500 BVs	Liu et al. 2019
		Filtrasorb 600, Calgon	NR	0.0506±0.0163	Coal SA_{BET}: 614 m^2/g	PFAS contaminated well water	NR	7.56	2.7	Ca 116.3 Mg 34.2 Na 105.1 S 72.11	Flow Through	0.17***	NA,NA	1.5 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~22500 BVs	Liu et al. 2019
		GAC400, Norit			Coal Effective size: 0.55-075 mm SA_{BET}: 963 m^2/g									2.25 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~20000 BVs	
		GCN1240, Norit			Coconut Effective size: 0.55-075 mm SA_{BET}: 1107 m^2/g									1.75 µg PFAS/g GAC at 5% breakthrough; initial breakthrough ~15000 BVs	
		Filtrasorb 400, Calgon	100 g	0.038-0.090	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 10597 BVs Average removal efficiency of 81%	McCleaf et al. 2017
		Filtrasorb 300, Calgon	100 mg	15000-150000	Effective Size: 0.8-1.0 mm Porosity: 0.627	DI Water (100 mL)	30	7.2 (3 mM PO_4^{3-})	NR	NR	Batch	48**	Langmuir, NA	Adsorption capacity 196.2^{a} 38.5^{b}	Ochoa-Herrera and Sierra-Alvarez 2008
		Filtrasorb 400, Calgon			Effective Size: 0.55-0.75 mm Porosity: 0.627									Adsorption capacity 236.4^{a} 60.9^{b}	
				12.4-290									Freundlich, NA	Adsorption capacity 25.9^{b}	
		URV-MOD1, Calgon		15000-150000	Effective Size: 1.10-1.18 mm Porosity: 0.592								Langmuir, NA	Adsorption capacity 211.6^{a} 36.7^{b}	

Chemical Tested	Sorbent Type	Name, Company	Sorbent Amount	[PFAS] μg/L	Sorbent Properties Reported	Matrix Tested	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium* or Experiment Time (hrs)** or Contact Time (hrs)***	Best Fit Isotherm, Kinetics	Result	Reference
PFOS (cont.)	GAC (cont.)	NR,NR	795.22 cm^3	0.55	Total pore volume: 0.865 cm^3/g Micropore volume: 0.354 cm^3/g SA_{BET}: 800 m^2/g	Reservoir water	22	7.2	4.5	NR	Flow Through	0.17***	NA,NA	Removal: DOC 4.5: 50% DOC 5: 48% DOC 10: 39% DOC 15: 30% DOC 20: 29% DOC 25: 28%	Pramanik et al. 2015
		Filtrasorb 400, Calgon	100 mg	10-5000	SA: 900-1,100 m^2/g	DI Water (100 mL)	25	6.4	NR	NR	Batch	<20*	Freundlich, NA	Adsorption capacity 28.4^{b}	Seneviranthna et al. 2010
		Filtrasorb 400, Calgon	5-25 mg	1000	Coal SA_{BET}: 924 m^2/g More meso-(2-50nm) and macropores (>50 nm) than coconut tested	Spiked DI water Spiked DI water w/1 mg/L PFOA (125 ml)	NR	7.2 (PO_4^{3-})	NR	NR	Batch	168**	Langmuir, NA	Adsorption capacity (single/mixed) 40.9/38.4^{a} 54.5/36.0^{b}	Siriwardena et al. 2019
		CBC-OLC 12X30, Calgon			Coconut SA_{BET}: 908 m^2/g More micropores <2 nm than coal tested									Adsorption capacity (single/mixed) 16.0/15.8^{a} 18.9/15.2^{b}	
		NR, Sinopharm Chemical Reagent Co.	10 mg	2000-250000	SA_{BET}: 712 m^2/g	DI Spike Water (100 ml)	25	Kinetic: 3 or 7 Isotherm: 5	NR	NR	Batch	168**	Langmuir, pseudo-second order	Adsorption capacity 161.5^{a} 0.47^{d}	Yu et al. 2009
	PAC	NR,NR	795.22 cm^3	0.55	Total pore volume: 0.365 cm^3/g Micropore volume: 0.154 cm^3/g SA_{BET}: 880 m^2/g	Reservoir water	22	7.2	4.5	NR	Flow Through	0.17***	NA,NA	DOC 4.5: 56% removal DOC 5: 55% DOC 10: 48% DOC 15: 37% DOC 20: 27% DOC 25: 21%	Pramanik et al. 2015
		NR, Sinopharm Chemical Reagent Co.	10 mg	2000-250000	SA_{BET}: 812 m^2/g	DI Spike Water (100 ml)	25	Kinetic: 3 or 7 Isotherm: 5	NR	NR	Batch	12**	Freundlich, pseudo-second order	Adsorption capacity 277.4^{a} 0.83^{d}	Yu et al. 2009
		NR, Sigma-Aldrich	2-20 mg	10-300	Particle size ≤ 40 μm, SA_{BET}: 763.8 m^2/g	Spiked DI, Wastewater (1L)	25	7.2 (1 mM PO_4^{3-})	7.3 (effluent)	NR	Batch	168**	Freundlich, pseudo-second order	Adsorption capacity DI: 17.475^{C} Wastewater: 2.250^{c}	Yu et al. 2012
	PAC (in a membrane bioreactor)	NR, Sigma-Aldrich	30-100 mg	200	Particle size ≤ 40 μm, SA_{BET}: 763.8 m^2/g	Wastewater	28	6.8-7.5	NR	NR	Flow Through	720**	NA,NA	~77.4-94.8% removed, increased w/ [PAC]	Yu et al. 2014
FOSA	GAC	Filtrasorb 400, Calgon	100 g	0.047-0.092	Coal Effective size: 0.55-0.75 mm Surface Area: 1050 m^2/g	Spiked drinking water	NR	8.3	1.8	Ca: 35 Cl: 64 F: 0.94 Mg: 17 Na: 31	Column	5208	NA,NA	10% column breakthrough at 10545 BVs Average removal efficiency of 80%	McCleaf et al. 2017

*: Equilibrium, **: Experiment time, *** Contact time (all in hrs)

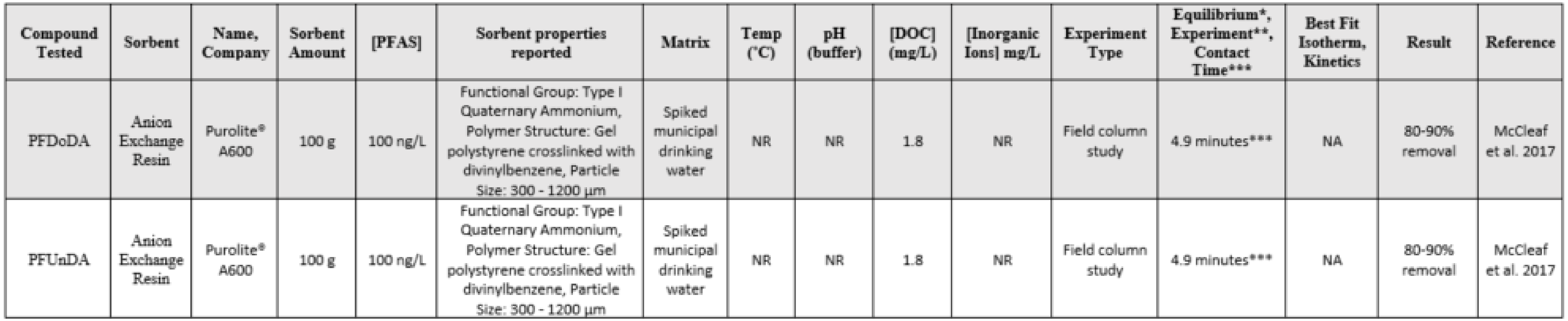
a: mg-PFAS/g-sorbent, b: (mg PFOS/g sorbent)(mgPFAS/l)$^{-n}$, c: (μg PFOS/mg sorbent)(L/μg PFAS)$^{1/n}$, d: mmol$^{(1-1/n)}$L$^{1/n}$ g^{-1}, e: mg^{1-a} L^{a}/kg

Table A-2. Anion Exchange Research Summary Results. EEC indicates Equilibrium Exchange Capacity. NR indicates not reported, NA indicates not applicable.

Compound Tested	Sorbent	Name, Company	Sorbent Amount	[PFAS]	Sorbent properties reported	Matrix	Temp (˚C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium*, Experiment**, Contact Time***	Best Fit Isotherm, Kinetics	Result	Reference
PFBA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	10% removal	McCleaf et al. 2017
		Purolite® A600E	1.0g	1000 mg/L	Polymer matrix: polystyrene-DVB, Porosity: gel-type, Functional Group: trimethyl quaternary amine	Spiked DI	20	7.5	NR	NR	Batch	144 hours**	NA	EEC: 19.1 mg/g	Zaggai et al. 2016
			350 mL	430 ng/L		Drinking water	NR	NR	NR	NR	Pilot test	10.1 minutes***	NA	EEC: 0.6 mg/g	
PFPeA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	23% removal	McCleaf et al. 2017
PFHxA	Anion Exchange Resin	Purolite® A600	400 mL	Low ng/L levels (ND-110 ng/L)	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Raw water	8.5	7.8	2.8 TOC	NR	Column study	12 weeks**	NA	73% removal	Franke et al. 2019
PFHpA	Anion Exchange Resin	Purolite® A600	400 mL	Low ng/L levels (ND-110 ng/L)	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Raw water	8.5	7.8	2.8 TOC	NR	Column study	12 weeks**	NA	100% removal	Franke et al. 2019
PFOA	Anion Exchange Resin	Purolite® A600	400 mL	Low ng/L levels (ND-110 ng/L)	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Raw water	8.5	7.8	2.8 TOC	NR	Column study	12 weeks**	NA	94% removal	Franke et al. 2019
		Purolite® A600E	1.0g	1000 mg/L	Polymer matrix: polystyrene-DVB, Porosity: gel-type, Functional Group: trimethyl quaternary amine	Spiked DI	20	7.5	NR	NR	Batch	144 hours**	NA	EEC: 125.2 mg/g	Zaggai et al. 2016
			350 mL	430 ng/L		Drinking water	NR	NR	NR	NR	Pilot test	10.1 minutes***	NA	EEC: 28.5 mg/g	
PFNA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	70-80% removal	McCleaf et al. 2017

Compound Tested	Sorbent	Name, Company	Sorbent Amount	[PFAS]	Sorbent properties reported	Matrix	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium*, Experiment**, Contact Time***	Best Fit Isotherm, Kinetics	Result	Reference
PFDA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	80-90% removal	McCleaf et al. 2017
PFBS	Anion Exchange Resin	Purolite® A600	400 mL	Low ng/L levels (ND-110 ng/L)	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Raw water	8.5	7.8	2.8 TOC	NR	Column study	12 weeks**	NA	100% removal	Franke et al. 2019
		Purolite® A600E	1.0g	1000 mg/L	Polymer matrix: polystyrene-DVB, Porosity: gel-type, Functional Group: trimethyl quaternary amine	Spiked DI	20	7.5	NR	NR	Batch	144 hours**	NA	EEC: 34.6 mg/g	Zaggai et al. 2016
			350 mL	430 ng/L		Drinking water	NR	NR	NR	NR	Pilot test	10.1 minutes***	NA	EEC: 2.8 mg/g	
PFHxS	Anion Exchange Resin	Purolite® A600	400 mL	Low ng/L levels (ND-110 ng/L)	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Raw water	8.5	7.8	2.8 TOC	NR	Column study	12 weeks**	NA	99% removal	Franke et al. 2019
			100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	≥90% removal	McCleaf et al. 2017
PFOS	Anion Exchange Resin	IRA67, Amberlite	10 mg	200-400 mg/L	Matrix: Polyacrylic, Porosity: Gel, Functional Group: Polyamine, Exchange Capacity: 5.6 meq/g, Particle Size (mesh) 16-50	Spiked DI	25	3	NR	0-100 mg/L sulfate 0-105.6 mg/L Cr(VI)	Batch	48**	Pseudo-second-order model	Adsorption capacity: 5.70^{a} Initial sorption rate: 0.76^{b}	Deng et al. 2010
		IRA958, Amberlite			Matrix: Polyacrylic, Porosity: Macroporous, Functional Group: Quaternary ammonium, Exchange Capacity: 3.7 meq/g, Particle Size (mesh) 16-50									Adsorption capacity: 4.86^{a} Initial sorption rate: 1.08^{b}	
		IRA96, Amberlite			Matrix: Polystyrene, Porosity: Macroporous, Functional Group: Polyamine, Exchange Capacity: 4.7 meq/g, Particle Size (mesh) 16-50									Adsorption capacity: 3.82^{a} Initial sorption rate: 0.21^{b}	

Compound Tested	Sorbent	Name, Company	Sorbent Amount	[PFAS]	Sorbent properties reported	Matrix	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium*, Experiment**, Contact Time***	Best Fit Isotherm, Kinetics	Result	Reference
PFOS (cont.)	Anion Exchange Resin	IRA400, Amberlite	10 mg	200-400 mg/L	Matrix: Polystyrene, Porosity: Gel, Functional Group: Quaternary ammonium, Exchange Capacity: 3.8 meq/g, Particle Size (mesh) 16-50	Spiked DI	25	3	NR	0-100 mg/L sulfate 0-105.6 mg/L Cr(VI)	Batch	48**	Pseudo-second-order model	Adsorption capacity: 0.53[a] Initial sorption rate: 0.01[b]	Deng et al. 2010
		IRA410, Amberlite			Matrix: Polystyrene, Porosity: Gel, Functional Group: Benzyldimethyl (2-hydroxyethyl) ammonium, Exchange Capacity: 3.4 meq/g, Particle Size (mesh) 20-50									Adsorption capacity: 0.73[a] Initial sorption rate: 0.03[b]	
		IRA900, Amberlite			Matrix: Polystyrene, Porosity: Macroporous, Functional Group: Quaternary ammonium, Exchange Capacity: 3.4 meq/g, Particle Size (mesh) 16-50									Adsorption capacity: 4.20[a] Initial sorption rate: 0.11[b]	
		Purolite® A600	400 mL	Low ng/L levels (ND-110 ng/L)	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Raw water	8.5	7.8	2.8 TOC	NR	Column study	12 weeks**	NA	99% removal	Franke et al. 2019
			100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	≥90% removal	McCleaf et al. 2017
		Purolite® A600E	1.0g	1000 mg/L	Polymer matrix: polystyrene-DVB, Porosity: gel-type, Functional Group: trimethyl quaternary amine	Spiked DI	20	7.5	NR	NR	Batch	144 hours**	NA	EEC: 186.2 mg/g	Zaggai et al. 2016
			350 mL	430 ng/L	Polymer matrix: polystyrene-DVB, Porosity: gel-type, Functional Group: trimethyl quaternary amine	Drinking water	NR	NR	NR	NR	Pilot test	10.1 minutes***	NA	EEC: 2.2 mg/g	
FOSA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	80-90% removal	McCleaf et al. 2017



Compound Tested	Sorbent	Name, Company	Sorbent Amount	[PFAS]	Sorbent properties reported	Matrix	Temp (°C)	pH (buffer)	[DOC] (mg/L)	[Inorganic Ions] mg/L	Experiment Type	Equilibrium*, Experiment**, Contact Time***	Best Fit Isotherm, Kinetics	Result	Reference
PFDoDA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	80-90% removal	McCleaf et al. 2017
PFUnDA	Anion Exchange Resin	Purolite® A600	100 g	100 ng/L	Functional Group: Type I Quaternary Ammonium, Polymer Structure: Gel polystyrene crosslinked with divinylbenzene, Particle Size: 300 - 1200 µm	Spiked municipal drinking water	NR	NR	1.8	NR	Field column study	4.9 minutes***	NA	80-90% removal	McCleaf et al. 2017

*: Equilibrium, **: Experiment time, *** Contact time

a: mmol PFAS/g-sorbent, b: mmol PFAS/g-sorbent/h

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6. AUTHORS

Nicholas T. Hayman
Jessica E. Carilli
Robert D. George
Lewis Hsu
Melissa A. Sanders
NIWC Pacific

Yina Liu
Michael Shield
Texas A&M University

Becca Morrison
San Diego State University Research Foundation

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14. ABSTRACT

This document details a literature review of current adsorbent technologies for PFAS-impacted groundwater treatment. It identifies data gaps that will be addressed in part through NESDI project 578.

15. SUBJECT TERMS

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