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Fluoroolefin-vinyl ether copolymer ionic fluorogels for PFAS remediation from water

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Per- and polyfluoroalkyl substances (PFAS) are a class of toxic chemicals that are ubiquitous in the environment and have contaminated water sources globally. As regulations limiting PFAS concentrations in drinking water are being established by regulatory agencies globally, there is an urgent demand for robust granular sorbents that remove PFAS from water selectively and are easily regenerated. Here we report a new class of Ionic Fluorogels (IF) that leverage fluoroolefin-vinyl ether (FVE) perfectly alternating copolymers as a polymer matrix for the development of ion exchange resins. The use of 2-chloroethyl vinyl ether as a comonomer provided a partially fluorinated polymer with electrophilic functionality, which was reacted with multivalent amines to install covalent crosslinks and cationic character in a single synthetic step. Systematic variation in the identity of fluoroolefin comonomer and multivalent amine resulted in a library of materials for structure–property evaluation. We found that the synergistic combination of a fluorophilic matrix and cationic charge leads to high PFAS sorption, and that the ratio of quaternary ammonium to tertiary amine is an important design criteria. Performance evaluation showed that the FVE-based IFs have high binding capacity for GenX, up to 770 milligrams GenX per gram IF, facile regeneration with no lapse in performance across five cycles, and higher PFAS selectivity than commercial ion exchange resin in both simulated and natural waters.

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Introduction

Per- and polyfluorinated alkyl substances (PFAS) are a class of fluorinated synthetic chemicals¹ which are used commercially in fluoropolymer manufacturing, waterproof coatings, food packaging, and aqueous fire-fighting foams (AFFF), among others.² PFAS have been associated with numerous claims of endocrine, reproductive, immunotoxic, and other health effects.^{3,4} In part due to their toxicity, “legacy” PFAS, such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), were phased out by 2006^{5,6} and replaced with “emerging” PFAS including perfluoroalkyl ether acids (PFECAs).^{7,8} Although understanding of the toxicity and bioaccumulation of emerging PFECAs like GenX is still nascent, a growing body of evidence indicates that PFECAs are concerns for human and animal health.⁹

In the United States, the U.S. Environmental Protection Agency (EPA) has investigated PFAS and determined that they are harmful to human health. In 2024, the U.S. EPA estab-

lished legally enforceable Maximum Contaminant Limits (MCLs) in drinking water for six PFAS: PFOA, PFOS, PFHxS, PFNA, GenX, and PFBS. The limits are 4 parts per trillion (ppt) for PFOA and PFOS, 10 ppt for PFHxS, PFNA, and GenX, and a hazard index of less than one for a mixture containing two or more of PFHxS, PFNA, GenX, and PFBS.¹⁰ While subsequently the U.S. EPA announced its intention to rescind the limits and reconsider the regulatory determinations for PFHxS, PFNA, GenX, and PFBS, the limits for PFOA and PFOS remain in place.¹¹ Public water utilities have until 2031 to implement PFAS remediation strategies and comply with the MCL. An estimated 7000 water utilities in the U.S. will have to install new water remediation systems or modify existing systems to meet the proposed MCLs, and the annual cost is estimated to be upwards of \$2.7 billion.¹²

Implementation of efficient, cost-effective PFAS remediation technologies is critical. Reverse Osmosis (RO) and nanofiltration efficiently remove PFAS from water, however, these processes are difficult to implement on large scales, as they create large amounts of PFAS-laden residuals, are energy intensive, and may not be cost-effective for impacted communities.¹³ Granular sorbents, such as granular activated carbon (GAC) and ion exchange resins (IX), have shown promise in pilot studies; however, they often demonstrate poor performance for short-chain PFAS such as GenX and other PFECAs.^{14,15} In one

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practical example, the Sweeney Water Treatment Plant in the impacted community of Wilmington, NC, installed a \$43 million system that removes PFECAs to low-ppt levels using 3 million pounds of GAC which is replaced every 270 days.¹⁶ The annual operating costs for this water treatment system are estimated at approximately \$5 million.¹⁷

The expense of PFAS remediation by traditional granular sorbents and the impending scope of remediation motivates the development of materials that are selective for fluorinated chemicals. An effective PFAS sorbent would have high PFAS selectivity over natural organic matter and other co-constituents in water, resulting in higher-capacity sorbent beds, long operational lifetimes, and less material usage. Regenerability constitutes an additional attractive feature of an effective PFAS remediation sorbent that yields a longer usage life cycle and a concentrated PFAS waste that can be destroyed using emerging destruction technologies.¹⁸ However, development of practical removal technologies relies on fundamental understanding of PFAS sorption processes. Taking inspiration from GAC, many materials leverage hydrophobic interactions to selectively partition PFAS from solution. Furthermore, molecular recognition^{19–23} and supramolecular host-guest complexes^{24–26} implemented *via* cationic crosslinked resins^{27–30} and porous polymer sorbents^{31–36} have demonstrated preliminary promise to remove PFAS from water. These materials often lack selectivity for a wide range of PFAS at environmentally relevant concentrations such as those in natural waters that serve as drinking water sources.³⁷

To address this lack of selectivity in natural waters, we were inspired by the use of fluorophilicity to selectively partition PFAS from aqueous solution.^{29,38–44} Previously, we reported Ionic Fluorogels (IFs), a selective class of PFAS remediation sorbents which leverage perfluoropolyethers (PFPEs) as fluorophilic matrices for PFAS removal. In a flow-through packed bed geometry, the IFs efficiently removed PFAS from natural waters spiked with part-per-trillion level PFAS, supporting our hypothesis that a synergistic combination of fluorophilic and electrostatic components enables high-performance PFAS remediation from natural waters (Fig. 1A).³⁹ However, PFPEs present some possible environmental hazards,⁴⁵ are expensive on scale, and suffer from hydrolytic degradation without chemical modification. Installation of aryl-ether linkages as PFPE end groups limited hydrolytic degradation (Fig. 1B),⁴⁶ but concerns regarding costs and potential environmental hazard remain. Given the need for a scalable and chemically-stable PFAS remediation technology, we hypothesized that a complementary class of partially fluorinated copolymers, fluoroolefin-vinyl ether copolymers (FVEs), could serve as low-cost, hydrolytically stable, high-performance fluorophilic matrices for PFAS removal (Fig. 1C).

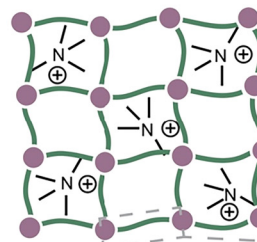
FVEs are tunable, partially fluorinated polymers synthesized through the perfectly alternating radical copolymerization of a fluoroolefin monomer and one or more vinyl ether monomers (Fig. 2A).^{47–49} The alternating character arises due to the difference in radical polarity^{50,51} between the fluoroolefin (*e.g.* tetrafluoroethylene, hexafluoropropylene, chlorotrifluoroethylene) and the vinyl ether (*e.g.* isobutyl vinyl

A. Previous work: IFs for PFAS remediation



- Synergistic combination of fluorophilicity & ion exchange
- Efficient PFAS sorption in complex matrices
- Hydrolytically degradable

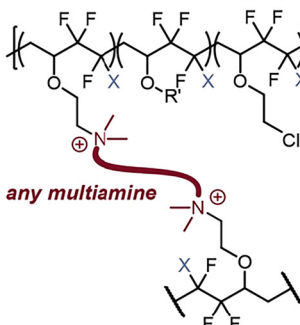
B. Previous work: Stable IFs for PFAS remediation



- Selective PFAS removal from natural N.C. water
- Regenerable in green solvent
- Quantitative PFAS removal in column tests
- Poorly defined stoichiometry
- low-volume starting materials



C. This Work: Fluoroolefin-Vinyl Ether IFs



- Selective for PFAS over non-fluorinated organic matter
- Regenerable in green solvent
- Highly tunable materials platform
- High-volume, low cost starting materials

Fig. 1 (A) Perfluoropolyether ionic fluorogels (IFs) demonstrated the concept of using fluorophilicity and ion exchange for PFAS sorption. (B) Second generation IFs are hydrolytically stable but remain cost and scale prohibitive for water remediation applications. (C) This work demonstrates the use of widely available and chemically stable fluoroolefin-vinyl ether copolymers for the development of a library of materials for PFAS remediation.

ether, chloroethyl vinyl ether) during propagation.^{48,52,53} Vinyl ethers are readily available, electron-rich monomers that do not homopolymerize through radical polymerization.^{54,55} Fluoroolefins are electron-deficient monomers that are polymerized at an industrial scale using radical polymerization. The matching of radical polarity leads to a lower kinetic barrier (ΔG^\ddagger) toward crosspropagation, which results in an alternating polymer microstructure.^{53,56–71} Incorporation of a functional comonomer such as chloroethylvinyl ether (CEVE) enables post-polymerization modification to form graft copolymers^{62,72} or ionomers,^{49,61} further diversifying the structural manifold provided by the FVE copolymer platform.

We leveraged functional CEVE to provide a platform for the generation of a library of polymer networks to evaluate for





Fig. 2 Synthesis of fluoroolefin-vinyl ether copolymers (FVEs). (A) Synthesis of fluoroolefin copolymers (FVEs) with chloroethylvinyl ether (CEVE), and/or isobutylvinyl ether (iBVE), and either hexafluoropropylene (X = CF₃) or chlorotrifluoroethylene (X = Cl). (B) Copolymers characterization. ^a kg mol⁻¹ as measured *via* SEC (THF, Refractive Index detector). Mol% = mole percent, M_n = number average molar mass, \bar{D} = dispersity.

PFAS remediation (Fig. 2B). Nucleophilic substitution of the alkyl chloride with tertiary amines results in formation of quaternary ammonium groups, installing both a covalent crosslink and permanent cationic character in a single synthetic step. We hypothesized that this new class of IFs would be efficient PFAS sorbents, as they would leverage both a fluorinated matrix and electrostatic interactions to remove PFAS from water.

Herein, we report FVE copolymer-based Ionic Fluorogels (FVE-IFs) as a library of granular resins for PFAS remediation. These modular materials demonstrate improved sorption of PFAS from simulated natural water relative to commercial ion exchange resins, high PFAS capacity, and facile regeneration. Competitive sorption experiments indicate that FVE-IFs show superior selectivity for PFAS over organic matter compared to a state-of-the-art ion exchange resin. The tunability and performance of FVE-IFs make them a promising platform for translationally relevant PFAS remediation technology.

Results and discussion

A significant advantage of the FVE-IF materials platform is the tunability of the FVE copolymer structure to access varied degrees of ionic content and fluorophilicity. To understand the effect of fluoroolefin identity and functional comonomer density, we first synthesized a representative suite of FVE copolymers by radical copolymerization (Fig. 2A). Hexafluoropropylene (HFP) and chlorotrifluoroethylene (CTFE) were identified as fluoroolefin monomers to modulate fluorophilicity by changing the backbone fluorination of the polymer. CEVE was chosen as the functional comonomer through which post-polymerization nucleophilic substitution would occur.⁴⁹ Two FVEs with 1 : 1 feed ratios of fluoroolefin

and CEVE were synthesized with different fluoroolefins to yield poly(HFP-*alt*-CEVE) and poly(CTFE-*alt*-CEVE) (Fig. 2B, entries 1 and 2). To investigate the role of functional comonomer loading, a terpolymer with a 2 : 1 : 1 incorporation of HFP, CEVE, and isobutylvinyl ether (iBVE) (poly[(HFP-*alt*-CEVE)-*co*-(HFP-*alt*-iBVE)]) was also synthesized (Fig. 2B, entry 3). At a multi-gram scale, all three copolymers were isolated in yields consistent with literature precedent⁴⁹ and at appropriate number average molar masses (M_n) for subsequent cross-linking reactions ($M_n = 10\text{--}20\text{ kg mol}^{-1}$).

The resulting FVE copolymers were crosslinked *via* substitution with multi-functional nucleophiles (Fig. 3A and Table 1), leveraging the CEVE comonomer as a functional handle. The parent FVE copolymers are soluble in common organic solvents, therefore the reaction proceeded readily in acetone following an adapted literature procedure (see SI for a detailed procedure).⁴⁹ Upon network formation, the reaction solution formed an insoluble gel. After reaction completion, the material was ground into a powder and purified *via* Soxhlet extraction in ethanol, followed by drying *in vacuo* at 50 °C. The products were obtained in quantitative yield. The FVE-IFs were characterized *via* scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) (Fig. S2–S4). SEM revealed the expected morphology of granular resins; the particles were irregularly shaped with significant crevices and other surface features but no observable long-range order or porosity in the micrometer range (Fig. 3B).

The library of FVE-IFs synthesized is shown in Table 1. The nucleophilic crosslinker loading is described by mole percent (mol%) incorporation relative to fluoroolefin repeat unit. Poly(HFP-*alt*-CEVE) was used as the primary FVE for FVE-IF synthesis due to safety concerns regarding transport and storage of CTFE.⁷³ However, representative experiments using poly(CTFE-*alt*-CEVE) to form FVE-IF-3 and FVE-IF-5 were successful, demonstrating the ability to synthesize FVE-IFs with diverse fluoroolefin monomers. Using *N,N,N',N'*-tetramethylethylenediamine (TMEDA) as a model nucleophile resulted in quantitative conversion of the soluble polymer to a crosslinked network, even when only 10 mol% of TMEDA was used (FVE-IF-1), or when CEVE incorporation was decreased (FVE-IF-6). Because a tertiary amine-based crosslinker was used, the nucleophilic substitution resulted in quaternary ammonium ion formation, such that network formation and permanent charge installation are achieved in one step. This represents an advance over existing technologies, which typically require separate reactions for network formation and quaternary ammonium group formation.

To investigate the effect of multiamine molecular weight and architecture, 1,1,4,7,7-pentamethyldiethylenetriamine (PMDTA), 1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA), and tris[2-(dimethylamino)ethyl]amine (Me₆TREN) were each used as multiamines for FVE-IF synthesis (FVE-IF-8, FVE-IF-9, FVE-IF-10, FVE-IF-11). Incorporation of fluorinated tetraethylene glycol (FTEG) as a secondary nucleophile also resulted in network formation (FVE-IF-4, FVE-IF-5). FTEG incorporation





Fig. 3 Synthesis of FVE-IFs. (A) Synthesis of FVE-IFs *via* nucleophilic substitution crosslinking. (B) SEM images of ground FVE-IF-2.

Table 1 Library of FVE-IFs

| Ref. | FVE | Multiamine | | mol% FTEG |
|------------------|---|----------------------|------|-----------|
| | | Identity | mol% | |
| FVE-IF-1 | Poly(HFP- <i>alt</i> -CEVE) | TMEDA | 10 | 0 |
| FVE-IF-2 | Poly(HFP- <i>alt</i> -CEVE) | TMEDA | 40 | 0 |
| FVE-IF-3 | CTFE- <i>alt</i> -CEVE | TMEDA | 40 | 0 |
| FVE-IF-4 | Poly(HFP- <i>alt</i> -CEVE) | TMEDA | 40 | 20 |
| FVE-IF-5 | Poly(CTFE- <i>alt</i> -CEVE) | TMEDA | 40 | 20 |
| FVE-IF-6 | Poly[(HFP- <i>alt</i> -CEVE)- <i>co</i> -(HFP- <i>alt</i> -iBVE)] | TMEDA | 40 | 0 |
| FVE-IF-7 | Poly(HFP- <i>alt</i> -CEVE) | TMEDA | 94 | 0 |
| FVE-IF-8 | Poly(HFP- <i>alt</i> -CEVE) | PMDTA | 37 | 0 |
| FVE-IF-9 | Poly(HFP- <i>alt</i> -CEVE) | HMTETA | 74 | 0 |
| FVE-IF-10 | Poly(HFP- <i>alt</i> -CEVE) | Me ₆ TREN | 20 | 0 |
| FVE-IF-11 | Poly(HFP- <i>alt</i> -CEVE) | Me ₆ TREN | 40 | 0 |

introduced an additional fluororous component to the FVE-IFs, which we hypothesized would further improve PFAS sorption.

The resulting FVE-IFs were first subjected to PFAS remediation batch experiments under equilibrium conditions in simulated natural water. The parameters of this experiment are described in the SI and our previous work.³⁹ Briefly, simulated natural water was prepared by dissolving 200 mg L⁻¹ NaCl and 20 mg L⁻¹ humic acid in deionized water. The salt content mimicked the salt content of natural water; however, the humic acid loading was one to two orders of magnitude higher than what would be expected in a practical remediation scenario, making this a challenging experiment for non-selective sorbents. Next, the sorbent (10 mg L⁻¹) was suspended in the solution, then stirred 3 hours to hydrate. Upon hydration,

the particles swelled marginally but retained the shape and structural integrity. For example, **FVE-IF-2** swelled ~50 wt% compared to its dry weight, which indicates that it is a loosely crosslinked polymer network (Table S2 and Fig. S5). Attempts to analyze their surface area through nitrogen adsorption were not successful, presumably because FVE-IFs behave like “gel” ion exchange resins with no permanent porosity. Finally, the solution was spiked with three representative PFAS at 1 μg L⁻¹ each, resulting in a 20 000 times excess of humic acid relative to each PFAS. After 21 hours of stirring, the solution was analyzed *via* Liquid Chromatography-Mass Spectrometry (LC-MS) to determine how much of each PFAS was removed by the sorbent. Control experiments without sorbent or with a commercial ion exchange resin were also performed. The figure of merit for this experiment is percent removal of each PFAS relative to a control with no sorbent present, where higher percent removals correlate to better sorbent performance (Fig. 4).

Batch equilibrium sorption results for the FVE-IFs revealed informative structure–property–performance relationships (Fig. 4). **FVE-IF-1**, with 10 mol% incorporation of TMEDA relative to repeat unit (equating to a maximum of 20 mol% incorporation of quaternary ammonium groups given TMEDA contains two tertiary amines), demonstrated poor PFAS removal. However, **FVE-IF-2**, with 40 mol% incorporation of TMEDA, demonstrated over 85% PFOA removal, 68% PFHxA removal, and 49% GenX removal. **FVE-IF-3**, synthesized using poly(CTFE-*co*-CEVE), demonstrated similar performance to **FVE-IF-2**, synthesized using poly(HFP-*alt*-CEVE), indicating there may be little to no effect on performance when replacing the HFP trifluoromethyl moiety with chloride. **FVE-IF-4** and





Fig. 4 Batch equilibrium PFAS sorption by FVE-IFs. Water constituents: 200 mg L⁻¹ NaCl and 20 mg L⁻¹ humic acid; pH = 6.4. Sorbent: 10 mg L⁻¹; PFAS: (PFOA, PFHxA, GenX, 1 μg L⁻¹ each). Equilibrium time: 21 h. Error bars: standard deviation of 3 experiments. Percent removal determined relative to controls without sorbent.

FVE-IF-5 performed similarly to **FVE-IF-2** and **FVE-IF-3** despite incorporation of FTEG. We reason that this similarity across four materials of the library indicates that small differences in fluorophilicity do not affect overall PFAS sorption under these challenging water conditions. **FVE-IF-6** also performed similarly to **FVE-IFs 2–5**, indicating that the incorporation of alkyl vinyl ethers does not reduce PFAS sorption. These initial results are encouraging, especially when compared to the high-performing commercial resin PFA694E (labeled IX in Fig. 4).

The use of FVEs as a platform enabled the incorporation of both quaternary ammonium and tertiary amine functionality into a single sorbent. In one approach, the incorporation of iBVE lowered the density of electrophilic sites (*i.e.* CEVE repeat units), which results in a lower number of reactive sites for nucleophilic substitution by tertiary amines (**FVE-IF-6**). The use of an FVE with 50 mol% CEVE relative to HFP repeat unit and the use of 40 mol% TMEDA results in an FVE-IF with 63% quaternary ammonium and 37% tertiary amine, assuming quantitative conversion of chloroalkyl group to ammonium. While **FVE-IF-6** performed similarly to resins with a high proportion of permanent positive charge, further reductions in quaternary ammonium density to 53% had adverse effects on short chain PFAS removal (**FVE-IF-7**). We infer from the contrasting results between **FVE-IF-6** and **FVE-IF-7** that there is some ratio of strong base to weak base ion exchange sites below which short-chain PFAS sorption is reduced. However, since PFOA sorption by **FVE-IF-6** and **FVE-IF-7** were similar, we hypothesize that long-chain PFAS sorption is driven by fluorophilicity, which increases with increasing perfluoroalkyl chain length.^{74–76} These trends are consistent with previous investigations with PFPE IFs.³⁹

Investigating other multiamine crosslinkers elucidated further structure–property–performance relationship trends. **FVE-IF-8**, which was crosslinked with 37 mol% PMDTA, demonstrated poor PFAS removal relative to its analog **FVE-IF-2** crosslinked with 40 mol% TMEDA. PMDTA has an

additional tertiary amine, which results in a higher crosslink density and higher density of quaternary ammonium groups. Finally, Me₆TREN, a tripodal multiamine crosslinker, was used in **FVE-IF-10** and **FVE-IF-11**. These two FVE-IFs had attractive sorption performance similar to **FVE-IFs 2–5**. **FVE-IF-10**, with 20 mol% Me₆TREN incorporation, 67% quaternary ammonium groups and 33% tertiary amines (presumably only the sterically accessible distal amines react), demonstrates efficient sorption of both long- and short-chain PFAS. **FVE-IF-11**, which has 63% quaternary ammoniums and 37% tertiary amines, also demonstrated efficient sorption. To understand how fluorine content influences adsorption, Table S2 correlates wt% fluorine in the FVE-IFs to equilibrium sorption. Taken together, these initial batch equilibrium sorption results demonstrate that both TMEDA and Me₆TREN serve as effective amines for high performance FVE-IF sorbents for PFAS removal, and that the ratio of quaternary ammonium to tertiary amine is an important design criteria to consider.

FVE-IF performance was investigated more thoroughly using **FVE-IF-2** as a model sorbent and GenX as a model PFAS. First, the kinetics of PFOA and GenX sorption by **FVE-IF-2** were investigated independently in pure water. At high concentration (200 μg L⁻¹ PFAS, 10 mg L⁻¹ sorbent), up to 93% GenX removal and 94% PFOA removal were observed (Fig. 5A). At low concentrations (1 μg L⁻¹), PFAS sorption was near-quantitative after 21 hours (Fig. S6), with 95% PFOA and 97% GenX removal observed. No significant PFAS desorption was observed throughout the course of this experiment. Although the kinetics of PFPE IF PFAS sorption are faster,³⁹ the performance of **FVE-IF-2** is promising as a proof-of-concept.

The ability to regenerate and reuse PFAS remediation sorbents is crucial for both fundamental insights, as well as practical performance. Fundamentally, observing the binding affinity of PFAS to a sorbent under different conditions elucidates structure–property–performance relationships. Practically, sorbent regeneration *via* an environmentally conscious solvent mixture enables desorption of PFAS into a concentrated solution which may be further analyzed or destroyed. Additionally, regeneration of the sorbent extends its lifetime, significantly decreasing technology ownership cost and improving overall performance. Therefore, we conducted repetitive sorption and desorption experiments using **FVE-IF-2** and GenX to probe the regenerability of the FVE-IFs. **FVE-IF-2** was suspended in a solution of GenX in nanopure water (target dosing was 10 mg GenX per gram of **FVE-IF-2**), stirred 1 hour, and centrifuged. The supernatant was analyzed *via* LC-MS to determine how much GenX was sorbed. The **FVE-IF-2** pellet was then suspended in a solution of 400 mM ammonium acetate in 50% aqueous ethanol, stirred 1 hour, and centrifuged. The supernatant was then analyzed to determine the extent of GenX desorption. The desorption brine solution was identified as a green alternative to harsher methanol-based regenerants used previously.³⁹ This process was repeated over five cycles in triplicate (Fig. 5B). The results show that **FVE-IF-2** is regenerable over at least five cycles with no decrease in sorbent performance.





Fig. 5 Kinetics, regeneration, and capacity of FVE-IFs. (A) Time dependent PFAS sorption by FVE-IF-2 at $[PFOA]_0 = 200 \mu\text{g L}^{-1}$ (red circles) or $[GenX]_0 = 200 \mu\text{g L}^{-1}$ (blue triangles); $[FVE-IF-2] = 10 \text{ mg L}^{-1}$; $\text{pH} = 9.7$. (B) Regeneration and reuse over 5 cycles of FVE-IF-2. $[FVE-IF-2] = 1.00 \text{ mg}$, target $[GenX]_0 = 10 \text{ mg L}^{-1}$ (1.00 mL); extraction with 400 mM ammonium acetate in 1:1 EtOH:H₂O (1.00 mL). Error bars: Standard deviation of 3 experiments. (C) GenX Sorption Isotherm by FVE-IF-2 ($[FVE-IF-2] = 100 \text{ mg L}^{-1}$; $[GenX]_0 = 0.2\text{--}50 \text{ mg L}^{-1}$); 21 h contact time. Lines show fit to Langmuir (red, solid) and Freundlich (blue, dashed) models.

The GenX binding capacity of FVE-IF-2 was measured by subjecting FVE-IF-2 to batch equilibrium sorption experiments in pure water spiked with a range of GenX concentrations ($[GenX]_0 = 0.2\text{--}50 \text{ mg L}^{-1}$). Binding capacity, typically measured in milligrams of analyte per gram of sorbent (mg g^{-1}), is a valuable metric for PFAS sorbents that indicates the maximum amount of analyte which can be sorbed to the resin at equilibrium. The amount of GenX sorbed to FVE-IF-2 at

equilibrium was plotted against the concentration of GenX remaining in solution for each experiment, then the data were fit to both the Langmuir and Freundlich isotherms (Fig. 5C). The calculated capacity for FVE-IF-2 was $770 \pm 50 \text{ mg g}^{-1}$ according to the Langmuir isotherm ($r^2 = 0.99$) (Table S2). This capacity is over 2.75 times higher than the calculated binding capacity for PFPE IFs (280 mg g^{-1}).³⁹

Despite only removing 50% of GenX in the batch sorption experiment in simulated natural water, FVE-IF-2 demonstrates outstanding GenX binding capacity in nanopure water. We hypothesize this disparity stems from some non-selective sorption of non-fluorinated organic matter by the FVE-IF. However, relative to commercial anion exchange resins, we hypothesized that the fluorinated matrix of the FVE-IF would result in improved selectivity for PFAS. To probe this difference in selectivity, we designed a proof-of-concept experiment which leveraged ¹H and ¹⁹F NMR to measure fluorinated and non-fluorinated organic matter binding. Solutions of about 3 mM of PFOA, GenX, octanoic acid (OA), hexanoic acid (HxA), PFOA and OA, and GenX and HxA were prepared. To 1 mL of each solution, 20 mg of either FVE-IF-2 or Purolite PFA694E was added. The resulting suspensions were stirred 1 hour, then transferred to 1.5 mL tubes and centrifuged. Next, 450 µL supernatant was spiked with 40 µL D₂O and 10 µL trifluoroethanol (as an internal standard), then the percent removal of each analyte was determined via ¹⁹F NMR (PFOA, GenX) and ¹H NMR (OA, HxA) relative to control reactions without sorbent. The results are summarized in Table S7 and Fig. 6. In experiments with only one analyte, FVE-IF-2 demonstrated

A. FVE-IFs demonstrate selectivity for PFAS



B. Competitive binding experiments



Fig. 6 Competitive binding of fluorinated versus non-fluorinated analytes. (A) Schematic representation of PFAS (green) binding to FVE-IF and IX relative to non-fluorinated organic matter (black). The FVE-IF is more selective for PFAS over organic matter than the IX. (B) Selected results from competitive binding experiments as determined via ¹H and ¹⁹F NMR. Sorbents subjected to mixtures of either PFOA and OA (left) or GenX and HxA (right). IX = Purolite PFA694E.



near-quantitative removal of PFOA and GenX, as measured by ^{19}F NMR, and no removal of OA or HxA, demonstrating significant selectivity for fluorinated analytes. Meanwhile, the IX removed all PFOA and GenX, as well as 43% of OA and 36% of HxA. In a mixed solution of PFOA and OA, **FVE-IF-2** removed all detectable PFOA and 31% of OA, while IX removed 100% of both PFOA and OA. Likewise, in a mixed solution of GenX and HxA, **FVE-IF-2** removed 98% of GenX and 31% of HxA, while IX removed 100% of GenX and 46% of HxA. Therefore, in a mixed solution of fluorinated and non-fluorinated organic matter, both **FVE-IF-2** and IX are more selective for fluorinated molecules. However, **FVE-IF-2** demonstrated significantly higher PFAS selectivity than IX, as evidenced by the results with mixed PFAS and non-fluorinated organic matter, in particular the PFOA and OA solution, and as supported by the superior **FVE-IF-2** performance in the batch tests with simulated natural water depicted in Fig. 4. Coupled with the high GenX binding capacity, the selectivity of FVE-IFs for PFAS makes them a promising class of materials for translational application to water remediation systems.

Conclusion

FVE copolymers are an underexplored class of functional materials. Here, we demonstrated a new class of Ionic Fluorogels that synergistically combine an FVE copolymer fluorinated matrix with ion exchange *via* cationic quaternary ammonium groups for selective PFAS remediation from simulated natural water. The resulting polymer networks are high-performing sorbents with excellent binding capacity for GenX as well as facile regenerability in a green solvent. Finally, when compared to commercial ion exchange resins under identical conditions, FVE-IFs outperform IX under both simulated natural conditions, and in high-concentration NMR studies. These FVE-IFs represent a significant advance in the development of translationally relevant PFAS sorbents, as the principles of Ionic Fluorogels have been demonstrated to be general across multiple classes of fluorinated polymers.

Conflicts of interest

Two international patent applications have been filed by the University of North Carolina at Chapel Hill on technology related to ionic fluorogels, including PCT/US2020/047365 and PCT/US2022/013249. F. A. L., O. C. and I. M. H. have a financial interest in Sorbenta Inc.

Data availability

The data that supports the findings of this study, including chemical and materials characterization, methods, and procedures, can be found in the supplementary information (SI). See DOI: <https://doi.org/10.1039/d5py00795j>.

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