

Best Practices for Experimental Design, Testing, and Reporting of Aqueous PFAS-Degrading Technologies

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ABSTRACT: Increased awareness of pervasive per- and polyfluoroalkyl substances (PFAS) contamination and the need for zero-pollution treatment solutions necessitate the scientific and engineering community to respond urgently and systematically. Existing approaches lack reproducible and standardized methods to report the technological treatment capabilities. Consequently, it is difficult to compare innovations and accurately assess their potential. In this Perspective, we shed light on hurdles encountered in the lab-scale research and development of aqueous PFAS destruction technologies with a focus on chemical methods and offer recommendations for overcoming them. Best practices are provided for developing robust PFAS laboratory protocols covering crucial aspects such as experimental planning, sample



storage and analysis, and waste management. Further, we present five criteria to standardize reporting on performance and advances in PFAS degrading technologies: 1) scope, 2) defluorination efficiency, 3) relative energy consumption, 4) material stability, and 5) unit process considerations. Through the dissemination of these insights, we aim to foster progress in the development of highly effective treatment solutions.

KEYWORDS: perfluoroalkyl substances, laboratory research, early stage development, technology comparison, reporting standards

1. INTRODUCTION

Concerns regarding per- and polyfluoroalkyl substances (PFAS) continue to grow as we have become more aware of their ubiquitous presence and mobility,¹ as well as the adverse environmental² and human health^{3,4} effects of certain PFAS. In Europe and North America, regulatory agencies continue to lower acceptable levels of PFAS in drinking water and other environmental matrices, driving the urgency to develop effective methods to remove and destroy PFAS.5-9 In this context, research into aqueous PFAS-degrading technologies, aiming to end the cycle of these forever chemicals, has surged and is summarized in several reviews.^{10–13} In addition, the focus has shifted from simple degradation that form secondary byproducts, which may also pose environmental threats,^{14,15} to complete defluorination and mineralization of PFAS to inorganic fluoride (F^-) , carbon dioxide, and water. In fact, several early stage destruction technologies have shown promising potential for PFAS defluorination.¹⁶ Yet, laboratory practices regarding materials and methods employed in the development, testing, and evaluation of these technologies vary widely among studies, leading to inconsistencies in reporting and difficulties comparing results. Thus, it is currently difficult to determine: What are the most promising solutions? How can results

be reliably reported? In which direction should development continue? and Where do opportunities for collaboration exist?

In general, laboratory research in PFAS degradation involves several steps in three experimental blocks, namely: (i) Planning, (ii) Operations, and (iii) Reporting results (Figure 1). Experimental planning comprises a statement of the aims of the study, research questions, identification of water matrix, number and types of PFAS, and initial concentrations, among other parameters. Initial experimental conditions must be assessed to identify the degradation method and practical applications of the technology. Although the use of high initial PFAS concentrations (μ g/L to mg/L) compared to reported environmental levels (pg/L to μ g/L)¹⁷ facilitates tracking of transformation products and fluoride concentrations during initial development, it compromises the evaluation of practical feasibility beyond the specialized treatment of concentrated

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Figure 1. Main steps in laboratory research and development of PFAS-degrading technologies.

waste streams.^{18,19} Furthermore, improper sample preparation and handling processes lead to cross-contamination, safety issues, inaccurate analyses, and ultimately misleading results. Selecting the appropriate instruments for analysis is critical for the validity and reliability. In particular, specialized methods are required for analyzing unknown PFAS to report destruction mechanisms²⁰ and including samples with complex water matrices or low PFAS concentrations,²¹ especially as technological development progresses.

During experimental trials, destruction technologies also produce PFAS-laden waste streams, e.g., pyrolysis liquid waste²² and incinerator scrubber water,²³ that must be accurately accounted for and properly managed, particularly given the high initial concentrations often tested. After all, the aim of PFAS destruction technologies research should be to end the cycle of PFAS contamination and not transfer the problem. This Perspective aims to assist researchers and practitioners in preparing lab-scale experimental plans, ensuring the reliability of results, and comparing high-performing technologies at initial technological readiness levels (TRL) of 1-3. To this end, we propose standardizing evaluation strategies in lab-scale testing via common reporting parameters for aqueous PFAS-degrading technologies with a focus on chemical methods aiming to achieve complete defluorination of PFAS. These suggestions will facilitate reliable comparisons among destructive technologies in terms of performance, energy efficiency, and practicality.

2. RECOMMENDATIONS FOR RELIABLE LAB-SCALE EXPERIMENTAL DESIGN OF PFAS DEGRADATION

2.1. Analyte Considerations. Analyte selection is a critical step to characterize PFAS-degrading technologies, since structural characteristics affect PFAS' physicochemical properties, such as adsorption affinity, stability, bond dissociation energies, and steric effects, which may restrict the defluorination reactions. For example, the average energy required for C–F bond dissociation in perfluorooctanoic acid (PFOA) is three times less than for perfluorooctanesulfonate (PFOS),²⁴ whereas PFOS adsorbs more strongly than PFOA because it has a longer perfluoroalkyl chain and a sulfonate functional group.²⁵ Yet, the continuous discovery of new PFAS^{26,27} complicates analyte selection. Additionally, analytical limitations impede detection and quantification of certain PFAS, especially of nonregulated compounds, for which analytical standards are rarely commercially available.

Consequently, identifying the aim of the study is a crucial first step to avoid misleading generalization. Thus, we propose three approaches. The minimum approach is to target the current or proposed regulations for a certain application, e.g., Danish drinking water guidelines for the total sum of PFOA, perfluorononanoic acid (PFNA), perfluorohexanesulfonic acid (PFHxS), and PFOS. However, by using this approach, there is a risk that the technology becomes inadequate, given the likelihood that additional compounds will be regulated in the future (e.g., short-chain PFAS). The second approach selects relevant compounds based on the targeted application and actual PFAS occurrences. For instance, the target analytes might be hexafluoropropylene oxide dimer acid (HFPO-DA, often referred to as GenX) and its degradation products when handling wastewater from fluoropolymer production,²⁸ whereas mixed perfluoroalkyl acids (PFAA) and their precursors would be the common targets at aqueous film-forming foam (AFFF) contaminated groundwater sites.²⁹ The third approach evaluates the broadness of the technology's application by testing a PFAS spectrum based on certain structural characteristics, such as chain lengths (e.g., perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), PFOA) or functional groups (e.g., PFOS vs PFNA). For example, UV/ sulfite systems exhibit variable degradation performances for PFAS with the same number of $(CF_2)_n$ units, depending on whether the compounds are perfluoroalkyl sulfonamide precursors (FASA), fluorotelomers sulfonates (FTSA), or perfluoroalkyl sulfonic acids (PFSA).³⁰ With this approach, the effects of the hydrophobicity/hydrophilicity, mobility, and molecular interactions in the degradation technology are evaluated, thereby elucidating the chemical structure's impact and facilitating comparison of different degradation methods. We strongly encourage combining the three approaches to holistically assess total PFAS, since this measurement has become increasingly important given the latest regulatory trends. This practice may also provide mechanistic insights and open new avenues for structure-independent degradation strategies.

In addition, valuable insights can be obtained by testing reference synthetic PFAS-spiked matrices to independently study the effect of relevant co-analytes (e.g., co-ions and natural organic matter^{31,32}) at lab-scale, which may enhance or inhibit the degradation process. For example, salts may quench the

photogenerated reactive species in photocatalytic systems,³³ while chloride salts may generate chlorine radicals, which are effective for PFOA degradation.³⁴ Nevertheless, PFAS research rarely reports co-analytes, limiting the selection to a few model substances in pure water.¹² Given the complexity of real water matrixes, new technologies should be tested with actual polluted waters to evaluate their intended applications.

2.2. PFAS Sample Integrity and Reliability. 2.2.1. Minimizing Adsorption to Materials. Preventing inadvertent adsorption of analytes to lab materials and experimental equipment is paramount to accurately assess PFAS degradation results. Common storage materials, sampling containers, vials, and filters may adsorb PFAS at relevant research concentrations, e.g., <500 μ g/L, leading to inaccurate reports of degradation performance.^{35–37} For example, long-chain PFAA have been found to adsorb onto polypropylene containers due to hydrophobic interactions between the polymer and the perfluoroalkyl tail.³⁸ Consequently, polystyrene is the preferred material for the storage of long-chain PFAA, compared to polyethylene, glass, polycarbonate, or polypropylene.³⁹ Yet the adsorptive behavior of short-chain PFAA differs,⁴⁰ making glass the preferable storage material for these compounds.³⁵ Furthermore, PFAS can adsorb to syringe filter material, with losses dependent on matrix; generally, recycled cellulose filters show the lowest adsorption for dissolved organic carbon (DOC) water and Milli-Q water matrices, whereas polypropylene filters perform best for methanol.⁴¹ Finally, temperature, pH, ionic strength, the presence of cations and natural organic material, as well as retention time can impact PFAS's tendency to adsorb to plastic containers.⁴²

Comprehensive information regarding the PFAS adsorption onto commonly used components of experimental equipment, including reactors, connectors, tubing, fittings, and valves, is lacking. This represents a significant knowledge gap, since it may imply critical sources of error when working with sensitive, highresolution analytical equipment. Thus, we encourage researchers to take corrective measures by selecting appropriate labware, conducting adsorption control trials, and performing mass balances to evaluate and minimize losses of relevant analytes (e.g., at least a single PFAS) to laboratory materials and setups.

2.2.2. Degradation and Volatility. The stability of PFAS is well-established and attributed to its strong C-F bonds in the fluorinated alkyl chain, yet precursor PFAS, certain functional groups, and hydrophilic sites are prone to undergo degradation.⁴³ At a minimum, we recommend storing samples in sealed, cold, and light-free conditions. The appropriate selection of analytes, materials, mixing and subsampling, and monitoring storage conditions may improve the reproducibility and reliability of PFAS lab tests. While PFSA and perfluoroalkyl carboxylic acids (PFCA) are relatively stable, precursor PFAS such as perfluorooctane sulfonamides (PFOSA) and perfluorooctane sulfonamidoethanols (PFOSE) diminished significantly with increased storage temperature.^{29,44} Hence, the preparation of fresh aqueous stock solutions for dilution and sample storage at below 4 °C is advised, while freezing may be appropriate for select analytes prepared in other solvents.^{45,46} Oxidative conditions (e.g., dissolved oxygen and light irradiation) may also impact the sample's stability, due to the generation of reactive oxidative species. Although these species are typically ineffective at initiating defluorination,^{47,48} during long-period storage, they may induce transformations of PFAS headgroups and promote the breakdown of precursors to other PFAS molecules,⁴⁹ which may result in biased analysis.

Additionally, loss to the vapor phase from aqueous solutions and vapor phase transformations appears to be possible for several neutral PFAS species,⁵⁰ particularly those containing alcohol groups.⁵¹ PFCA and fluorotelomer alcohols (FTOHs) have also been detected in headspace when handling AFFF.⁵ Further insights on PFAS volatility and aerosol formation are needed to establish effective operational guidelines and develop reliable methods for the quantification of airborne PFAS. Monitoring concentrations of PFAS and fluorinated compounds (e.g., HF and trifluoroacetic acid (TFA)) in the headspaces of closed systems or exiting air in open systems,⁵³ under various environmental conditions (e.g., temperature, co-ions, concentration), is crucial to the accuracy of experimental data and to obtain reliable fluorine mass balance. Besides, it is also important to minimize human exposure to and inhalation risks of these compounds during or after the experiments.⁵⁴

3. RECOMMENDATIONS FOR ANALYZING PFAS DEGRADATION RESULTS

3.1.1. Implementing Target and Nontarget Analysis. The analysis of target PFAS based on liquid chromatographytandem mass spectrometry (LC-MS/MS) can refer to the US EPA published methods: "Method 537", "Method 533", and "Method 1633" in 2018, 2019, and 2024 to provide reliable determination of 40 PFAS in water using offline SPE in conjunction with LC-MS/MS, with detection limits in the low parts per trillion (ng/L) range. $^{\rm S5-57}$ While chromatography-MS methods provide highly accurate and sensitive PFAS measurement, they often require time-consuming and costly analyses, limiting frequent testing and onsite monitoring. The limitations of MS-based technologies make the development of inexpensive, user-friendly, yet sensitive assays for PFAS detection essential. Portable sensors are being developed as promising alternatives for PFAS analysis.⁵⁸ However, challenges, such as selectivity to detect PFAS in complex matrices⁵⁹ and high background concentrations of ultra short-chain PFAS like TFA,⁶⁰ must be overcome to ensure their adaptability for field use.

In most PFAS degradation studies, target analysis using LC-MS/MS provides concentration profiles of specific PFAS. However, to elucidate the transformation and degradation pathways, comprehensive analysis of unknown intermediates is essential. Suspect analysis is conducted when the sample can be screened for suspected compounds from existing databases.³⁰ Nontarget analysis (NTA) is a powerful technique, revealing a broad spectrum of unknown compounds in a sample.⁶¹ Highresolution mass spectrometry (HRMS) is a robust technique for PFAS nontarget analysis, enabling precise mass-to-charge ratio (m/z) measurement, using analyzers with an improved sensitivity and resolution over MS/MS, such as time-of-flight (ToF), Orbitrap, or Fourier transform ion cyclotron resonance.⁶² HRMS full-spectral data of each analyte provide excellent mass accuracy and isotopic fidelity and find fragmentation patterns, aiding in chemical identification within a defined confidence level.^{63,64} To overcome the high instrument costs that hinder the widespread adoption of NTA, we suggest a more widespread collaboration between analytical and technical laboratories. Furthermore, collaborative research can contribute to the development of suspected compound databases based on the sample source and/or treatment type, thereby simplifying identification efforts.

3.1.2. Conducting Fluoride Analysis and Fluorine Balance. Accurate determination of the F^- concentration is critical to assess defluorination. Fluoride analysis is primarily

performed by ion selective electrodes (ISE) or ion chromatography (IC).⁶⁵

The US EPA recommends fluoride ISEs for measuring total solubilized F^- in surface water, groundwater, and wastewater (SW-846 Test Method 9214).⁶⁶ While ISEs are compact and cost-effective compared to competing techniques, they are fragile and must be handled carefully to prevent electrode damage. Furthermore, ISE results must be interpreted cautiously due to the potential analytical interferences that can affect the measured concentration.⁶⁶ Most interferences can be mitigated by either adding appropriate chemical reagents (e.g., total ionic strength buffer) to the sample or replicating the background matrix during treatments.

To improve reliability, it is advisable to use both ISE and IC measurements, especially when working with complex matrices. Fluoride detection limits for IC analysis vary depending on the resin's selectivity and competing inorganic ions. For example, acetate (CH₃COO⁻) and formate (HCOO⁻), other byproducts of PFAS degradation,^{67,68} elute shortly after inorganic F⁻, complicating peak deconvolution and interpretation. The pH and ionic strength also affect the sample interaction with the column resin, altering retention times. Hence, appropriate dilutions are advised to prevent these effects and prolong the lifetime of the analytic column. Column sensitivity and peak retention times should be closely monitored, as even slight changes can lead to drastically different interpretations of the defluorination rate. Finally, pairing IC with a mass spectroscopy detector improves measurement quality over more widely used conductivity detectors.^{69–71}

To monitor the PFAS degradation and defluorination, both LC-MS/MS and IC results are analyzed. However, other fluorinated byproducts are often unaccounted for in these analyses, hindering a complete fluorine mass balance,⁷²⁻ which would validate proposed destruction methods and reaction pathways. Combustion ion chromatography (CIC) can detect total fluorine (TF) content by subtracting the inorganic fluoride from TF yielding the total organic fluorine (TOF).⁷⁵ Known PFAS and fluorinated compounds are deducted from TOF to quantify unidentified organic fluorinecontaining compounds; however, it does not provide structural information regarding the specific compounds present.⁷⁶ Employing organic solvent extraction allows further categorization into extractable organic fluorine (EOF) and nonextractable organic fluorine. Consequently, the TF, TOF, and EOF provide a more detailed depiction of the fluorinated pollutants properties present.⁷⁵ Environmental epidemiologists already employ these categorization techniques to detect various fluorinated compounds and assess whether PFAS exposure is underestimated.^{77–79} Additionally, a total oxidizable precursor (TOP) assay can be used to quantify oxidizing unknown precursor PFAS by converting them into stable PFAS which can be analyzed using target analysis.^{80,81} However, the TOP assay for environmental samples has limitations, including the formation of unmeasurable intermediates and variable results influenced by sample matrix, which can compromise accuracy of results.⁸² Meanwhile, including GC-MS analysis provides data on volatile species, such as PFAS alcohols, amides, and acrylates, for which there is limited information on their environmental fate and transport.⁸³ Finally, due to its ability to detect ultrashort-chain and nonionizable PFAS, ¹⁹F NMR analysis can further aid in closing the mass balance, though this technique is restricted by higher detection limits (in the μ g/L range) compared with LC-MS/MS.⁸⁴ Innovative strategies, such

as noise reduction and using a relaxation agent, are applied to enhance the sensitivity of NMR measurements to achieve a ng/L detection limit.^{85,86} Since fluorinated byproducts are usually not monitored in PFAS degradation studies, it raises the question of whether the effectiveness of these technologies could be overestimated. Therefore, it is strongly recommended that the mass balance of fluorine be conducted when evaluating PFAS treatment technologies, and the pursuit of additional, easy-touse analysis methods is encouraged.

4. HANDLING OF PFAS WASTE

Although destruction technologies aim to minimize fluorinated pollution, PFAS-laden waste is inevitably generated during research and development. Improper handling of these wastes could result in possible exposure and point-source contamination. Yet, disposal of waste from PFAS-degradation experiments and analysis procedures is rarely discussed in the literature, leaving individual research groups to create their own protocols. To ensure safe transportation and proper disposal of the generated waste, research centers must partner with qualified hazardous waste handling providers. These facilities typically incinerate waste in a rotary kiln, which operates at 1000-1200 °C, supposedly sufficiently high temperatures to destroy most persistent organic pollutants.⁸ However, to destroy the recalcitrant C-F bonds of PFAS, theoretical calculations demonstrate that achieving sufficient temperature, residence time, and turbulence during incineration is crucial.^{88,89} In practice, it is still unclear whether any PFAS,⁹ CHF_3 (a greenhouse gas),⁹¹ or volatile organofluoride decomposition byproducts are ending up in combusted solids (slag and ash), flue gases, and flue gas condensate, and whether fluorinated pollutants in these waste streams can be accurately measured by current collection and analysis methods.⁹²

Nonetheless, preventing the unintentional release of PFAS starts with robust waste collection practices in the laboratory. PFAS-laden wastes generated in the lab include both liquid waste and solid wastes, which often have different collection requirements. Liquid wastes are sorted depending on whether the PFAS is dissolved in an aqueous or organic solution and collected in high density polyethylene or polypropylene screwtop containers, which should be stored in ventilated waste cupboards to prevent possible exposure. Until waste can be collected, full containers should be stored in an exterior hazardous waste shed in collection containers containing vermiculite in order to adsorb any spills or leaks due to changing temperatures or movement. Since expired stock solutions represent a significant portion of high concentration PFAS liquid waste, thoughtful experimental planning and collaboration among researcher groups are encouraged to avoid generating unnecessary PFAS wastes. The use of out-ofdate stock solutions during preliminary testing or system optimization would further reduce the waste.

On the other hand, PFAS-laden solid waste is often mixed with other chemically contaminated solid waste, including filters, syringes, pipette tips, sample tubes and vials, adsorptive media, and soils, which are typically disposed of in plastic bags. Compared to screw-top containers, plastic bags are prone to tear and provide a weaker barrier to PFAS exposure. Thus, it is advised to use thicker safety gloves for their high-purity PFAS products due to their fast breakthrough time for standard 0.1 mm nitrile gloves. Therefore, the use of heavy-duty waste bags is advisable, as well as minimizing the presence of liquid residuals in the solid waste stream via evaporation in a fume hood and



Figure 2. Five features for comparative reporting of PFAS-degrading technologies.

proper liquid waste handling. Ultimately, it is mandatory for reference standard providers to provide safety data sheets (SDS), which are essential parts of the work safety protocol.

Finally, accounting for PFAS in generated waste streams is critical for assessing new technologies based on adsorptive catalysts (e.g., catalytic resins, activated carbons, and metalorganic frameworks (MOFs)) considering that undegraded PFAS ultimately remain in, for instance, regenerative solutions and adsorptive media. Not only do these waste streams constitute an immediate source of hazardous waste, they also present a significant problem during technology scale-up and should be included in life cycle analysis (LCA) and costing (LCC).⁹³ Thus, we urge the development of new analytical methods for detecting nonaqueous PFAS in the various waste streams generated, e.g., adsorptive catalysts and pyrolysis oils. The US EPA's posting of Other Test Method (OTM)-45 and OTM-50 are a promising start to standardize analysis methods of gaseous emissions.^{94,95} Yet, further work is required for reliable PFAS analysis in other phases or solvents.

5. ESSENTIAL REPORTING PARAMETERS FOR COMPARING PFAS DEGRADING TECHNOLOGIES

Unstandardized reporting of key parameters hinders the ability to compare the effectiveness of different technologies presented in the literature. Identifying criteria to effectively assess PFASdegrading technologies is challenging due to their disparate presentation, different experimental considerations, and varying operational requirements and scales. To overcome this challenge, we propose five defining features as minimum reporting guidelines to describe PFAS degrading technologies. These features include the scope, defluorination efficiency, relative energy consumption, material stability, and unit process considerations (Figure 2). The first recommended parameter is the scope, which should ideally be defined during the experimental planning. In order for treatment methods to be comparable, they must have common research parameters, i.e., targeted analyte types, chemical purities and concentrations, water matrix, type(s), and breadth of application. Nonetheless, the appropriate applications and research questions may evolve during the technology's development, and therefore, the scope needs to be clearly stated when reporting.

The second feature is defluorination efficiency, defined as the percentage of fluoride atoms eliminated from the PFAS parent compound during degradation, given by eq 1.

Defluorination (%) =
$$\frac{C_{\text{aqueous } F^-}}{N_F \times C_{\text{aqueous PFAS}}} \times 100\%$$
 (1)

where $C_{\text{aqueous }F^-}$ represents the final F^- concentration (M), $C_{\text{aqueous PFAS}}$ represents initial PFAS concentration (M), and N_{F} represents the number of fluoride atoms in a PFAS molecule. As an important step in determining the fluorine mass balance, defluorination efficiency levels the comparison between destructive technologies by providing a numerical comparison based on the initial PFAS-bound fluorine versus the final released fluorine, which can then be related to the energy input for this transformation. Defluorination efficiency indicates whether the technology is on track to mineralize a specific parent PFAS and eliminate its fluorinated byproducts. For instance, short-chain PFAS generated during incomplete PFAS destruction are associated with increased solubility, mobility, and energy requirement for mineralization, while still exhibiting toxicity and bioaccumulation potential.⁶⁰ Therefore, it is crucial that research shifts its focus from degradation performance to defluorination efficiency, aiming to ensure that only innocuous species (e.g., aqueous F^- , H_2O , and CO_2) are released into the

environment. The final F^- concentration must be below the regulatory level of 0.7 mg/L,⁹⁶ and the generation of secondary inorganic pollutants like perchlorate, due to intensive treatment reactions, should be monitored. We propose to test a single PFAS at a time to accurately track the defluorination kinetics and the maximum defluorination rate. Likewise, testing the performance of both short- and long-chain PFAS relevant to the intended application and water matrix defined in the scope should be presented as performance-determining parameters for all PFAS-degrading technologies.

Third, the evaluation of energy consumption in PFASdegrading technologies is often overlooked or inadequately characterized. Previous studies have generally reported the power consumption of the equipment and the defluorination achieved within a specified period and treated volume of PFAScontaminated water. However, the defluorination performance is also influenced by other parameters such as the initial PFAS concentration(s) and structural type(s). The system-dependency accentuates the need to establish parameters to relate the energy invested to the amount of F⁻ released from a model PFAS (such as PFOS), i.e., the electrical energy per order of bonded fluorine removed ($E_{EO,F}$, given by eq 2).⁷³

$$E_{\rm EO,F}\left(\frac{\rm kWh}{\rm m^3}\right) = \frac{P \cdot t}{V \cdot \log\left(\frac{1}{1 - deF}\right)}$$
(2)

where *P* is the power (kW), *t* is the treatment time (h), *V* is the treated water volume (m³), and *deF* is the defluorination efficiency, respectively. Note that the power was calculated from the total applied potential, not based on measured anode potentials. Therefore, we advocate the expanded use of $E_{\rm EO,F}$ as a defining feature to determine the comparative energy consumption for defluorination technologies.

Fourth, the assessment of the robustness of PFAS degrading technologies is limited by the lack of a single defined stability parameter that encompasses different mechanisms, conditions, and materials used. Generally, degradation processes introduce an energy source (e.g., voltage, light, heat) and may involve the addition of chemicals as well.⁹⁷ Hence, researchers should report on the leaching potential of the components under realistic operational conditions. These components include, for instance, the catalysts and dopants in photocatalysis, electrode materials and coatings in electrocatalysis, vessel materials in supercritical water reactors, or sonicator probes in ultrasonication processes. Although fluoropolymers (e.g., polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), fluoroelastomers (FKM/FPM)) are chemically stable, the potential of releasing fluoride ions or small molecular-weight fluorinated chemicals should not be excluded especially when exposed to intensive treatments such as high temperature.^{98,99} In addition, Joudan et al. report that laboratory polymers, including fluoropolymers (e.g., PTFE, perfluoroalkoxy alkane, and fluorinated ethylene propylene) and nonfluorinated polymers (e.g., polyvinyl chloride, polypropylene, and polyether ether ketone) released C_2-C_4 PFCA into water when extracted via sonication at room temperature.¹⁰⁰ This release may originate from their synthetic production processes such as the use of processing aids, residuals, and inhibitors. Thus, the use of fluorine-containing materials should be avoided if possible,¹⁰¹ or at a minimum evaluated with blank tests, to eliminate the unintentional introduction of fluoride to the system. Addition of fluoride may result in inaccurate defluorination measurements, especially when testing low-concentration PFAS.

Finally, studies should consider the need for associated unit processes, as they can impact the overall treatment train, implementation costs, and spatial requirements when scaling up the technology. For example, certain technologies such as hydrothermal, 102 thermal, 103 and sonication 104 processes are promising in terms of defluorination efficiency, but their application is limited to the treatment of concentrated streams due to high energy demands. Therefore, these types of technologies require preconcentration, while other technologies, like photocatalysis, require a postfiltration process to separate catalyst particles. Early identification and lab testing of pre- and postunit processes support reporting on the technology's overall operating requirements, energy consumption, and environmental LCA and LCC,^{105,106} which increasingly are expected as necessary components of funded research projects. It is important to consider that as the TRL advances, process and energy costs may be reduced but may create new challenges for waste management. Finally, the materials used in associated unit processes and their potential interaction with PFAS and byproducts, for instance, adsorption or aggregation at surface interfaces, also need careful evaluation.

6. IMPLICATIONS

Developing PFAS-degrading technologies requires robust experimental planning, an informed selection of analytes, and consideration of appropriate storage and operating conditions, in order to monitor losses and eliminate any negative inferences. As the technology advances, experiments should include tests conducted under more realistic conditions, namely, multicomponent water matrices at environmentally relevant concentrations. Nonetheless, it is acknowledged that the analysis of PFAS, their degradation products, and total PFAS is challenged by detection limits, instrument sensitivities, and *ex-situ* methods. While recommendations are offered for the most common analysis methods, we advocate for additional research into new detection techniques, particularly the use of portable sensors and the analysis of PFAS in other phases or solvents.

Meanwhile, knowledge sharing on the proper handling and disposal of PFAS-laden wastes is crucial to ensure that research groups mitigate any risk of PFAS release. Finally, we encourage standardized reporting through five criteria, which allow diverse PFAS-degrading technologies to be compared based on their scope, defluorination efficiency, relative energy consumption, materials stability, and need for pre- or post-treatment. It is essential to evaluate new technologies relative to one another to determine their merits and feasibility to end the PFAS cycle forever.

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Notes

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Environmental Science & Technology

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