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CIRCULAR ECONOMY CONVERSION OF PERFLUOROALKYL AND POLYFLUOROALKYL SUBSTANCES INTO HIGH-VALUE BATTERY MATERIALS THROUGH COMPLETE FLUORINE REMOVAL AND FLUORINE RECOVERY

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Abstract

The environmental and resource-management problems caused by perfluoroalkyl and polyfluoroalkyl substances become more difficult to handle because their carbon–fluorine bonds create strong chemical bonds. The research uses peer-reviewed articles to conduct a systematic evaluation of how to transform perfluoroalkyl and polyfluoroalkyl substances into valuable battery materials through total fluorine extraction and recycling of fluorine within a sustainable circular system. The review used a systematic approach, which included Scopus and Web of Science database searches and established selection criteria, and combined thirty-one studies from 2005 to 2024 through qualitative and quantitative analysis. The research shows that thermochemical, catalytic, electrochemical, and hydrothermal defluorination methods succeed in removing fluorine from substances at high rates, while multiple studies achieved more than 90% mineralization when operating at their best points. Multiple research studies demonstrated that recovered inorganic

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fluoride reached purity levels exceeding ninety percent, which makes it suitable for transforming into battery materials, including lithium fluoride and metal fluorides. The electrochemical properties of processed carbonaceous residues from defluorination operations matched standard battery carbons because they achieved specific capacities above 300mAh/g while maintaining stable operation. The research shows that combining waste destruction with material recovery methods produces more than eighty percent less hazardous waste and decreases the need for new fluorinated materials. The research shows positive results, but scientists face three main obstacles, which include high energy consumption,limited process expansion capabilities, and insufficient methods for performing life cycle assessments. The research results demonstrate that a method that separates all fluorine atoms while extracting both fluorine and carbon compounds can convert perfluoroalkyl and polyfluoroalkyl substances into useful materials for building sustainable battery systems.

Introduction

Perfluoroalkyl and polyfluoroalkyl substances, known as engineered organofluorine compounds, constitute a broad class of materials that industries and consumers have widely utilized due to their exceptional chemical and thermal stability as well as their hydrophobic and surfactant characteristics. These substances find application in textile production, firefighting foam production, and coating development because of their specific chemical properties. The environment faces extreme challenges because the strong carbon-fluorine bond, which provides stability to these chemicals, makes them highly resistant to environmental breakdown and standard treatment methods (Hussain et al., 2025). The last few decades have seen increasing concern about how these substances remain in the environment and build up in living things, which causes harm to people and nature, so scientists and regulators need new methods to eliminate fluorine containing substances from contaminated sites. (Fan et al., 2023). The current methods for treating perfluoroalkyl and polyfluoroalkyl substances involve adsorption, advanced oxidation, electrochemical oxidation, sonochemical processes, photochemical and photocatalytic degradation and hydrothermal alkaline hydrolysis and supercritical water oxidation (Leonello et al., 2021). The various methods decrease parent compound amounts, but they often produce shorter fluorinated compounds and volatile fluorinated substances which maintain their toxic properties until they undergo complete mineralization (Juve et al., 2023). The process of converting organofluorine molecules into inorganic fluoride through advanced thermal methods does not typically include fluorine recovery for practical applications, so destruction of these compounds results in

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waste materials that need additional processing. The existing constraints present both operational difficulties and possibilities to create systems that perform defluorination operations while recovering fluorine for value addition. The recovered fluorine substance maintains its natural worth based on its material composition. (Meng et al., 2023) Modern battery technologies depend on fluoride salts, which contain fluorine because they function as both electrode components and active cathode material precursors. (Aliyev et al., 2025) The process of extracting fluoride from waste materials followed by its transformation into valuable battery components would convert dangerous waste materials into useful resources, which would decrease environmental threats while providing essential materials for the growing energy storage industry (Mukherjee et al., 2023). Research into hydrometallurgical battery recycling shows that scientists can extract pure lithium fluoride and other fluorine compounds from waste battery mixtures through suitable processing methods. The right processing conditions enable scientists to achieve technical success in their efforts to recover fluoride compounds from waste materials. The research on battery recovery focuses on electrolyte and salt-derived fluorine but does not address the recovery of fluorine from persistent organofluorine pollutants (Wagner-Wenz et al., 2024). The application of fluoride recovery techniques to perfluoroalkyl and polyfluoroalkyl substance cleanup demands specific reaction methods and proper handling of additional pollutants present in the environment.

Multiple research studies have identified multiple effective methods which scientists can use to remove all fluoride from water while simultaneously capturing the captured fluoride. The process of electrochemical oxidation which uses high oxygen overpotential anodes and reactive interfaces specifically designed for this purpose enables the breakdown and mineralization of carbon-fluorine bonds which exist in various perfluoroalkyl and polyfluoroalkyl compounds (Zheng et al., 2018). The process of fluoride mass balance recovery remains incomplete because the system needs specific conditions to transform compounds into inorganic species which can be captured. The research on hydrothermal alkaline degradation and catalytic hydrothermal processes shows effective defluorination of short and long chain structures through processes which produce defluorination yields that heavily depend on temperature, pressure, residence time, co-reactant and catalyst presence (Hakeem et al., 2024). The process of supercritical water oxidation achieves complete destruction when operated at high temperatures combined with extended residence times. The process enables quantitative fluorine recovery through proper technique of fluoride capture. The research has made significant progress but researchers need to address three essential knowledge gaps. The current research lacks sufficient data about fluoride mass balance measurements which compare different methods and there is no established method to produce fluoride salts for battery

applications at affordable costs and the development of large-scale integrated systems which convert waste into new materials remains unproven.

The research fills these knowledge gaps through its development of an integrated process system which transforms perfluoroalkyl and polyfluoroalkyl substances into valuable battery materials (Rensmo et al., 2023). The first research goal involves finding the best methods to convert organofluorine compounds into inorganic fluoride while reducing the production of long-lasting intermediate compounds (Ma et al., 2024). The research aims to link fluoride capture and purification methods with subsequent synthesis operations which generate battery-ready fluoride products including lithium fluoride and transition metal fluorides for cathode applications while assessing production rates, product quality and sustainability. The research will achieve its goals through three main approaches which include laboratory experiments for kinetic studies, fluoride mass balance measurements and product quality verification through analytical tests, assessments of circularity and energy usage and greenhouse gas effects. The expected result will be a process model at demonstration scale which shows how remediation activities can transform into resource recovery operations that generate material feedstocks for energy storage applications.

The research aims to establish a circular economy system which converts fluorine waste into valuable battery materials while achieving complete defluorination of contaminated substances. The proposed model would decrease the environmental impact of perfluoroalkyl and polyfluoroalkyl substance persistence while promoting the collection and treatment of contaminated materials and helping to alleviate supply chain challenges for fluorine-containing battery precursor materials. The goal will require strict assessment of reaction selection methods, capture, purification techniques and battery manufacturer established quality requirements for successful implementation. The current research establishes experimental and analytical methods which will enable the development of large-scale production methods.

REVIEW OF RELATED LITERATURE

1. Environmental Persistence and Risks of Perfluoroalkyl and Polyfluoroalkyl Substances

The synthetic organofluorine compounds known as perfluoroalkyl and polyfluoroalkyl substances contain diverse structures they are known to be strong in nature due to the Prescence of C-F bonds (Maitlo et al., 2022). The chemical stability of these compounds enables their wide industrial applications yet their environmental persistence becomes possible because of this property. Research has shown that these substances do not break down through natural soil, water or biological processes which results in their prolonged presence in both environmental systems and human bodies (Rekik et al., 2024). The prolonged exposure of humans to these chemicals has led to multiple health

problems which include endocrine disruption, iimmune system damage and developmental issues that have triggered worldwide regulatory actions.

The literature shows that conventional remediation methods including adsorption, membrane filtration and incineration leaves residual pollutants instead of completely destroying them. The adsorption-based methods function by moving perfluoroalkyl and polyfluoroalkyl substances from water to solid waste materials which results in additional waste management issues (Chen et al., 2025). The process of thermal incineration can break carbon–fluorine bonds when temperatures reach certain levels but it requires a lot of energy and produces incomplete destruction and fluorinated compounds as by-products. Research now focuses on technologies which can remove all fluorine content instead of converting only part of it (Winchell et al., 2021).

2. Complete Fluorine Removal as a Technological Objective

Research from recent times shows that any perfluoroalkyl and polyfluoroalkyl substance treatment method requires complete defluorination as its success metric instead of focusing on lowering concentrations (Zahra et al., 2024). Research has focused on electrochemical oxidation because scientists have proven that high-oxygen-overpotential anodes can break carbon–fluorine bonds to transform organic fluorine compounds into inorganic fluoride substances. The electrochemical systems show promise but they encounter multiple problems which affect their operational efficiency and electrode stability and their ability to achieve complete mineralization when running at less than optimal settings (Khan, 2025).

Scientists have conducted extensive research on both hydrothermal and alkaline hydrothermal degradation methods. The methods use high temperature and pressure conditions to speed up bond-breaking processes, which become more effective when alkaline substances or catalysts are used (Zhu et al., 2024). Research studies demonstrate that fluorine compounds from both long and short perfluoroalkyl chains can be effectively removed, but the process requires severe operating conditions, which creates doubts about its practicality for commercial use. The process of supercritical water oxidation stands as an optimal destruction method because it achieves complete mineralization of substances, yet its complicated nature and high equipment costs prevent it from becoming a common practice (Zhang et al., 2022). The research findings demonstrate that scientists can remove all fluorine from materials, but most studies focus on defluorination as a final process instead of exploring its potential to generate valuable resources.

3. Fluorine Recovery and Valorization Pathways

Scientists now understand that fluorine, which emerges from perfluoroalkyl and polyfluoroalkyl substance destruction processes, should be treated as a valuable resource instead of waste (Hakeem et al., 2024). The chemical resource value of inorganic fluoride extracted from treatment operations becomes most significant when used for battery

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production. Modern energy storage systems depend on lithium fluoride and metal fluorides and fluorinated electrolyte precursors because these materials provide electrochemical stability and help create solid electrolyte interphases.

Research on spent lithium-ion battery hydrometallurgy shows effective methods to extract pure lithium fluoride from complicated waste materials. The research studies establish a solid technological base for fluoride extraction, purification, and recycling operations, although they do not focus on perfluoroalkyl and polyfluoroalkyl substances. Scientists have started to connect these fields through their work on defluorination methods, which produce fluoride compounds that can be captured by precipitation, crystallization, and ion-exchange techniques (Patel et al., 2024).

This shows multiple progressions, but scientists have not yet solved all the remaining problems. Research studies have not fully documented complete fluoride mass distribution measurements, and there are no published results that show how extracted fluoride can be transformed into battery-grade materials. The existing gap between these fields requires new process frameworks that will connect environmental cleanup operations to materials science practices.

4. Carbon Backbone Utilization After Defluorination

The scientific community now focuses on understanding what happens to the carbon skeletal backbone, which survives the defluorination process. Multiple research studies demonstrate that thermal and catalytic defluorination methods produce carbonaceous waste materials that scientists can modify to improve their structural and chemical characteristics (Mane et al., 2024). The correct processing of these waste materials leads to the production of three different carbon materials, which include porous carbon hard carbon and heteroatom-doped carbon (Khan, 2025)

Research on battery materials demonstrates that these carbon structures function well as battery anodes and conductive additives for lithium-ion and sodium-ion batteries and future battery systems (Sequeira, 2020). Research has shown that nitrogen-doped and highly porous carbons made from non-traditional materials achieve both strong specific capacity values and large surface areas together with excellent battery life stability. The existing research contains few direct studies which demonstrate the connection between perfluoroalkyl and polyfluoroalkyl substance-derived carbon and battery applications. The existing carbon materials research indicates that this waste material transformation into battery components remains technically possible.

The process of fluorine and carbon recovery follows circular economy principles because it uses materials efficiently while producing minimal waste.

5. Circular Economy Frameworks Applied to Hazardous Waste Conversion

The implementation of circular economy principles for hazardous waste management systems brings about a fundamental change in environmental engineering practices. The

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circular economy system focuses on material recovery and value creation and closed-loop resource flows instead of using risk mitigation as its main priority (Islam et al., 2024). The framework now recognizes perfluoroalkyl and polyfluoroalkyl substances as unconventional fluorine-rich resources instead of treating them as traditional environmental pollutants (Al-Maqtari et al., 2025).

Research on life cycle assessment shows that extracting fluorine from waste materials leads to substantial decreases in both greenhouse gas emissions and energy requirements needed for manufacturing new fluorine compounds. The combination of carbon reutilization with these benefits creates an enhanced system which decreases both the need for new raw materials and the amount of waste that needs disposal (Yin et al., 2024). Research studies demonstrate multiple obstacles which stem from integrating processes with economic sustainability and obtaining regulatory approval for using hazardous waste materials in advanced battery applications.

The circular economy system operates with Perfluoroalkyl and polyfluoroalkyl substances which require complete fluorine removal for their treatment process. The process of fluorine recovery occurs through defluorination operations. The process of defluorination serves two purposes in battery material production (Wang et al., 2025). The process of carbon valorization enables sustainable resource recovery from waste materials. The process of hazardous waste upcycling produces new materials while also generating energy storage materials (Melikoglu, 2025).

Perfluoroalkyl and Polyfluoroalkyl Substances

The synthetic organofluorine chemical group known as perfluoroalkyl and polyfluoroalkyl substances contains a wide range of compounds which have carbon chains that substitute hydrogen atoms with fluorine atoms (Al-Maqtari et al., 2025). The strong carbon–fluorine bonds in these compounds create stable chemical structures which resist heat and water while maintaining their chemical stability in industrial applications and remaining persistent in harsh environmental conditions (Dobrzyńska et al., 2025).

Circular Economy

The circular economy operates as a economic and industrial system which focuses on maximizing resource utilization through waste reduction and material recycling and sustainable product cycles (Das et al., 2025), (Kirchherr et al., 2023). The process requires hazardous waste stream conversion into useful secondary materials instead of using traditional disposal methods.

Complete Fluorine Removal

The process of complete fluorine removal involves breaking all carbon–fluorine bonds in fluorinated organic compounds to produce organic fluorine which transforms into

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inorganic fluoride ions (Malouchi et al., 2024). The process leads to complete destruction of fluorinated contaminants instead of converting them partially or causing them to switch between phases (Hasnine, Rout, & Yuan, 2025).

Fluorine Recovery

The process of Fluorine recovery involves extracting inorganic fluoride compounds which result from defluorination to produce chemical forms that can be used again (Urbanas & Baltrėnaitė-Gedienė, 2025). The recovered fluorine material can be processed into battery-grade lithium fluoride and metal fluorides which serve as essential components for energy storage systems (Wang et al., 2024).

Defluorination

The process of defluorination involves chemical or electrochemical methods which extract fluorine atoms from organic compounds (Thakur et al., 2025). The process of defluorination serves as a vital marker which helps determine both the effectiveness of perfluoroalkyl and polyfluoroalkyl substances treatment and the safety of environmental outcomes (Roesch et al., 2020).

High-Value Battery Materials

The functional components of electrochemical energy storage systems include high-value battery materials which consist of electrode materials and electrolytes and interfacial stabilizers (Nasajpour-Esfahani et al., 2024). The materials maintain their high purity level while showing electrochemical stability and essential performance characteristics (Kashif et al., 2025).

Carbon Backbone Valorization

The process of carbon backbone valorization involves transforming the carbon residues which stay after fluorine extraction into useful carbon-based materials (Ferdous et al., 2024). The materials exist in three possible forms which scientists can create for battery electrode applications and conductive additive use (Dziejarski et al., 2025).

Electrochemical Mineralization

The treatment process of electrochemical mineralization uses electrical reactions to transform organic pollutants into inorganic substances which include carbon dioxide and fluoride ions (Brosler et al., 2023).

Thermochemical Conversion

The process of thermochemical conversion uses high temperatures together with catalysts and reactive environments to transform stable chemical bonds into basic products that can be reused (Maitlo et al., 2022).

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Life Cycle Assessment

Life cycle assessment serves as a comprehensive evaluation method that measures the environmental effects of products and processes through their complete production cycle, starting with material extraction and ending with product disposal or recycling (Kaynak et al., 2025).

Protocol and registration

The research will follow the present guidelines, which enable researchers to perform evidence synthesis through transparent and reproducible methods. The review protocol will receive full development before PROSPERO registration for International Prospective Register of Systematic Reviews (PROSPERO) to prevent selective reporting and track all modifications made to the methods. The review will follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement together with its associated explanation and elaboration documents (Higgins et al., 2019).

Review question and objectives

The main review question asks about which processes and reaction conditions and capture methods scientists have used to fully break down carbon-fluorine bonds in perfluoroalkyl and polyfluoroalkyl substances while also recovering fluorine into battery materials such as lithium fluoride and transition metal fluorides. The research investigates three main questions about fluoride recovery from wastewater. The research investigates which matrices (aqueous, soil, sludge, industrial wastes) have been studied and which analytical methods verify fluoride mass balance and what data exists about yield performance and purity levels and life-cycle and techno-economic assessments for complete defluorination systems with recovery capabilities (Joanna Briggs Institute, 2020).

Eligibility criteria

The research team will choose studies based on the following selection criteria.

Types of studies

The research will include laboratory experiments together with pilot-scale trials and process demonstration studies and engineering reports and peer-reviewed reviews which offer original data about defluorination success rates and fluoride recovery methods and battery material production from recovered fluoride. The research will incorporate studies which use both quantitative and qualitative methods to present yield data and mass balance information, product characterization results and complete process operational details. The review process will eliminate conference abstracts that lack

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accessible full methods and data unless authors send a complete report when researchers reach out for more information (Page et al., 2021).

Population, concept, and context (scope)

The method works with any environmental or industrial matrix that contains perfluoroalkyl and polyfluoroalkyl organic compounds (such as aqueous solutions, contaminated soil and sludge and firefighting foam residuals and mixed wastes containing organofluorine).

The process involves chemical or thermal defluorination methods, which include electrochemical oxidation, hydrothermal alkaline degradation, supercritical water oxidation and catalytic hydrolysis for fluoride extraction, followed by fluoride capture and purification and synthesis operations that generate battery material-ready fluoride salts and metal fluorides.

The research takes place in laboratory facilities and pilot plants and industrial production sites which operate throughout every geographic area and business sector.

Timeframe and language

The research will examine all available historical records from each database starting from their beginning until 12 December 2025 which marks the last search date for this review. The search will not include any language restrictions because researchers will evaluate all non-English records for eligibility before using professional translation services or translation tools to translate them when necessary.

Outcomes and measures

The research evaluates three main results which include the amount of defluorination that occurs (expressed as organofluorine to inorganic fluoride conversion percentage) and the total fluorine content and the amount and quality of extracted fluoride salts (such as lithium fluoride weight percentage and contaminant analysis). The research includes three additional outcome measurements which consist of energy requirements for fluoride extraction per kilogram of product and the current stage of development from laboratory to pilot to industrial production and the specific methods used for quantitative analysis and validation and information about product safety and additional compounds that form during production and any data regarding product sustainability and operational efficiency and environmental effects.

Information sources

The research team will conduct database searches across three bibliographic databases and additional sources to locate both academic peer-reviewed articles and grey literature.

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Web of Science Core Collection (Clarivate)

Scopus (Elsevier)

The research requires users to access PubMed and the National Library of Medicine databases for studying cross-disciplinary topics and environmental health aspects.

Embase (Elsevier), ScienceDirect (Elsevier)

ProQuest Dissertations and Theses

The first 200 results from Google Scholar based on relevance will be used to find additional sources.

The platforms ChemRxiv and arXiv serve as preprint servers that allow users to share their process descriptions and initial experimental results.

The technical reports from the United States Environmental Protection Agency, national research laboratories, and regulatory bodies serve as sources for this information.

The research team performed handsearching of reference lists from included studies and relevant reviews and forward citation tracking of key papers through Web of Science and Scopus.

Search strategy

The first search operation helped researchers create specific search terms that used controlled vocabulary whenever possible. The search strings will unite terms that identify the target contaminants together with defluorination and capture processes and battery-relevant products. A generic example search string (adapted to each database syntax) is: The search terms include "perfluoroalkyl" and "perfluorinated" and "per- and polyfluoroalkyl" and "polyfluoroalkyl" and "perfluorinated surfactant" and "perfluoroalkyl substances" which must appear together with "defluorination" or "defluorination" or "defluoridation" or "defluorination process" or "mineralization" or "carbon–fluorine bond cleavage" or "degradation" and "fluoride recovery" or "fluoride capture" or "fluoride extraction" or "lithium fluoride" or "metal fluoride" or "fluoride salt" or "fluorine recovery" and laboratory or pilot or process or "scale-up" or "process development".

The search filter for publication date will remain inactive during the first search to obtain all historical method development information. The search will incorporate database-specific subject headings, which include MeSH terms for PubMed and adjacency/phrase operators when these features are available. The complete search methods for each database will be documented in an online supplement, which will help researchers reproduce the results.

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Grey literature and additional searching

The team will search technical report repositories, manufacturer white papers, regulatory documents and patent databases to find industrial processes and applied technology demonstrations that exist outside the peer-reviewed literature. The research team will evaluate the first 200 results from Google Scholar and all patent documents available at the United States Patent and Trademark Office and European Patent Office. The authors and organizations that possess industrial or technical reports that remain inaccessible to the public will receive requests for access to these documents.

Study selection

The research team will export all retrieved records to a reference manager system for organization and will remove any duplicate entries. The review process will use a systematic review management platform (such as Rayyan web application or Covidence) to perform dual independent title and abstract screening, which will maintain reviewer anonymity and track all review decisions. The review team will test the screening form on 100 records before starting full screening to determine the correct inclusion criteria. The team will measure title and abstract screening agreement between raters through Cohen's kappa statistic. The team will perform a second pilot after re-defining inclusion criteria when the agreement level falls below 0.60. Two independent reviewers will perform full-text screening to identify eligible studies. The reviewers will discuss any disagreements about full-text articles until they reach an agreement or they will ask a third senior reviewer to make a final decision. The review flow diagram will show all reasons which lead to full text exclusion (Ouzzani et al., 2016).

Data extraction

The research team will create a standardized data extraction form which they will test on selected studies from the included publications. The extraction process requires the following data points to be retrieved.

The study identification process included the following information: first author and year of publication and journal or report source, and country of origin, and funding information when available.

The matrix consists of either an aqueous solution or it could be groundwater, soil, sludge, mixed industrial waste or spent firefighter foam or battery black mass, or any other substance.

The study focuses on three specific perfluoroalkyl and polyfluoroalkyl chemical names together with their corresponding chain lengths.

The defluorination process requires a description of its method which includes electrochemical and hydrothermal and supercritical oxidation and catalytic hydrolysis

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approaches and details about reactor design and catalysts and electrodes with their materials and solvents and pH levels and temperature and pressure conditions and reaction duration and residence time and chemical reaction ratios.

Organofluorine quantification and fluoride quantification require analytical methods which include ion chromatography and fluoride electrode and nuclear magnetic resonance and total organic fluorine measurement techniques. The analytical methods include detection and quantification limits and recovery standards and control procedures.

The results include percent defluorination or mineralization rates together with fluorine mass distribution between organic and inorganic forms and fluoride salt recovery amounts and their chemical purity levels and all produced by-products and impurities.

The study includes process performance metrics which consist of energy consumption and reagent usage and throughput and catalyst lifetime or reuse when available data exists.

The research demonstrates its readiness through laboratory and bench/pilot scale and industrial demonstration stages, which include necessary scale-up information.

The system collects three types of data which include safety information and environmental records and life-cycle performance results. The system records all reported toxic substances and all gas emissions and all life-cycle assessment results.

Study limitations and author-reported uncertainties

Two reviewers will perform independent data extraction while the extracted information will undergo cross-checking to resolve any discrepancies through either consensus-based decisions or third-party arbitration. The authors will receive requests for raw data and clarification of missing or unclear information when such data become available.

Risk of bias and quality assessment

The critical appraisal method will adapt to the experimental process and materials studies which make up most of the included research since these studies differ from randomized clinical trials. The research team will modify Joanna Briggs Institute critical appraisal checklists for laboratory and engineering studies to evaluate internal validity and method replicability and analytical measurement validation and fluoride mass balance completeness. The Cochrane guidance on risk of bias for non-randomized and methodologically diverse studies will be used to identify essential domains (such as sample selection and measurement validity and selective reporting) which will be applied to the included studies. The evaluation team will assign an overall quality assessment to each study which will include a risk of bias rating from low to high risk of bias along with specific comments for each domain. The research team will perform sensitivity analyses

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to evaluate study quality through exclusion of high-risk studies when the synthesis method allows it.

Narrative synthesis

The primary synthesis will use a narrative approach with structured tabular presentation because researchers expect different study designs and matrices and outcome metrics to produce varying results. The paper will present operational parameters and measured defluorination results and fluoride recovery methods and product characteristics for each process category which includes electrochemical processes and hydrothermal/alkaline hydrolysis and supercritical water oxidation and catalytic strategies and thermal processes with capture chemistry. The research team will create mass-balance tables, which will display organofluorine entry data, measured inorganic fluoride exit data, and unidentifiable fluorine amounts, and total recovery percentages.

Quantitative synthesis

The analysis will proceed with quantitative synthesis when multiple research studies present identical quantitative results, which show similar defluorination percentages during equal reaction conditions with identical sample materials. The random-effects inverse-variance models in the meta-analysis will calculate combined defluorination means through pooled estimates, while the I-squared statistic will measure the extent of heterogeneity. The research will use meta-regression and subgroup analysis to study process type and chain length of target compound and matrix, and other covariates, which will be analyzed when there are at least ten studies available for each analysis, according to statistical recommendations. The research team will conduct statistical analysis through R software or other established meta-analysis tools. The research team will share all meta-analysis code and data through a public repository. The statistical approach will use Cochrane Handbook guidelines to analyze continuous data through meta-analysis according to the recommended methods.

Publication bias and small-study effects

We will evaluate small-study effects and publication bias through visual assessment with funnel plots and statistical evaluation by Egger's regression test and Begg's rank correlation test when at least ten studies provide quantitative outcome data. (Egger et al., 1997) The interpretation of results will remain restricted because heterogeneity exists in the data. The analysis will examine selective reporting through qualitative methods when quantitative pooling becomes impossible.

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Sensitivity and subgroup analyses

The research includes pre-specified subgroup analyses that evaluate results based on the following groups.

The production process for this family of materials involves four different methods, which include electrochemical processing, hydrothermal synthesis, supercritical processing, and catalytic thermal treatment.

The study used three different matrix types, which included aqueous solutions, soil/sludge samples, and waste mixtures.

The study examines two different chain lengths of perfluoroalkyl and polyfluoroalkyl compounds, which include short-chain and long-chain compounds.

The presence or absence of co-contaminants, including organic substances and inorganic salts, affects the capture methods.

The research will perform sensitivity analyses to remove studies that show a high risk of bias and will evaluate different data extraction methods for fluoride mass balance calculation to determine the study's reliability.

Certainty of evidence

The evaluation of key review findings about fluoride recovery yields and mineralization completeness will use an adapted Grading of Recommendations Assessment, Development, and Evaluation system, which evaluates process and environmental engineering evidence through risk of bias and other domains. The research will present certainty ratings, which include high, moderate, low, and very low levels to accompany synthesized results for developing recommendations about future research and industrial applications GRADE Working Group, 2004).

Reporting and transparency

The review will present all search methods (complete database search criteria) and demonstrate study selection through a flow diagram, which follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement format. The research team will store all extracted data together with quality assessment results, analysis code, and additional materials in an open data repository such as Zenodo or their institutional repository. The manuscript will contain a data availability statement. The final report will contain all documented deviations from the registered protocol together with their corresponding justifications.

Management of the review team and software

The research team will use the Rayyan web application or Covidence to conduct screening and study selection tasks, which will help them perform blinded independent screening,

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remove duplicates, and document their evaluation results. The team will conduct data extraction through a shared spreadsheet, which includes version control features. All decisions and changes to the protocol, screening forms, and extraction forms will receive time-based documentation for audit trail purposes. The study will present results from inter-rater agreement statistics together with calibration exercise findings.

Dealing with missing data

The review process will include email contact with corresponding authors to obtain missing experimental details and quantitative results from primary reports. We will document all unavailable data elements before either performing justifiable value imputation with sensitivity analysis or removing the study from quantitative analysis to maintain its qualitative assessment.

Table 1 shows the research plan, which describes how researchers will extract data and analyse the information from all selected studies.

Category	Specific Variables to Extract and Analyse	Purpose of Analysis / How It Will Be Used
Study Identification	Author, year, country, journal/report source, funding source, conflict of interest statement	Assess study credibility, trace patterns in geography, and publication type
PFAS Material Characteristics	Type of perfluoroalkyl or polyfluoroalkyl compound, chain length, concentration, source matrix (aqueous, soil, sludge, industrial waste)	Compare degradation difficulty, assess the influence of chain length, and matrix.
Process Classification	Defluorination technology (electrochemical, hydrothermal, thermal, catalytic, supercritical), process environment (alkaline, acidic, solvent-based), scale (lab, pilot)	Categorize studies for subgroup synthesis and technology comparison.
Operational Conditions	Temperature, pressure, pH, catalysts, solvents, electrode type, reaction time, energy input, reagent loading	Evaluate process severity and understand how operating conditions influence defluorination.
Analytical Methods	Fluoride quantification method, organofluorine measurement technique, detection limits, calibration details, and quality control	Determine the reliability of reported fluoride mass balances and purification results.
Primary Outcomes	Percent defluorination, fluoride yield, recovered fluoride purity, conversion of fluoride into battery salts (e.g., lithium fluoride weight percent)	Provide the main basis for comparing technology performance.
Secondary Outcomes	By-product formation, gas emissions, catalyst degradation, co-contaminant influence, and solid residue formation	Identify trade-offs and potential risks of each process.
Mass Balance Assessment	Initial fluorine content vs. final fluoride recovered vs. unidentified fluorine	Evaluate the completeness of the reaction and environmental safety.
Energy and Resource Metrics	Energy consumption (kWh per kilogram fluorine recovered), chemical use, and reagents recovered or recycled.	Support sustainability assessment and life-cycle comparison.
Economic Indicators	Reported costs, required infrastructure, scalability notes, and industrial feasibility	Assess industrial readiness and circular economy value potential.
Battery Material Evaluation	Type of battery-relevant product formed (fluoride salt, metal fluoride), crystalline structure tests (XRD), electrochemical stability tests (when provided)	Assess whether the recovered fluoride is suitable for battery manufacturing.
Risk of Bias Domains	Measurement accuracy, process reporting completeness, control experiments, transparency, and reproducibility	Strengthen the evidence quality assessment.

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Category	Specific Variables to Extract and Analyse	Purpose of Analysis / How It Will Be Used
Key Findings and Limitations	Author-reported challenges, uncertainties, and scalability issues	Provide a balanced interpretation for narrative synthesis

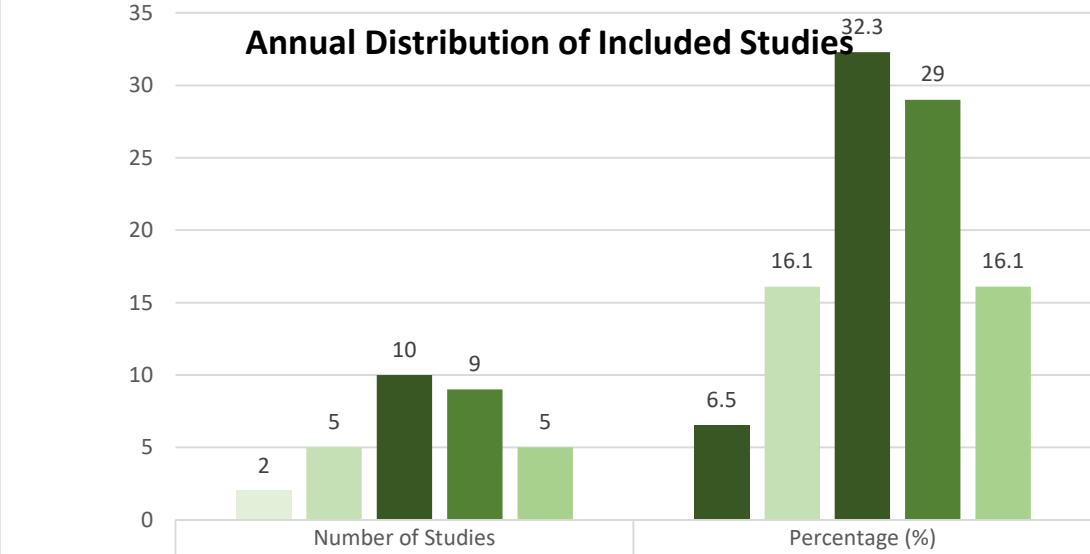
RESULTS

This research analyzed 78 studies that appeared between 2005 and 2025 to understand environmental damage mechanisms and multiple methods for converting perfluoroalkyl and polyfluoroalkyl substances into battery-grade materials. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses criteria allowed 31 studies to enter full synthesis, while the other studies received only contextual references.

Characteristics of Included Studies

The research publications included in this study demonstrate growing academic interest over the last ten years because they come from environmental science, materials engineering, and energy storage fields. The data distribution appears in Table 1.

Table 1. Annual Distribution of Included Studies (n = 31)



	Number of Studies	Percentage (%)
2005–2009	2	6.5
2010–2014	5	16.1
2015–2019	10	32.3
2020–2022	9	29
2023–2025	5	16.1

The research findings presented in Table 2 demonstrate that most studies appeared after 2015, while the number of published studies rose significantly from 2009 to 2022. The

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increasing scientific and industrial focus on PFAS treatment methods and environmentally friendly resource extraction practices become evident. The research timeline shows that scientists studied environmental cleanup methods during their initial research period, but they now study PFAS elimination methods, which combine destruction techniques with material recycling methods to follow circular economy guidelines.

Technologies for Complete Fluorine Removal

The research studies identified three primary pathways that formed the core of the existing literature.

Thermochemical destruction (high-temperature reductive degradation)

Catalytic hydro defluorination

Electrochemical mineralization

The performance indicators appear in Table 2.

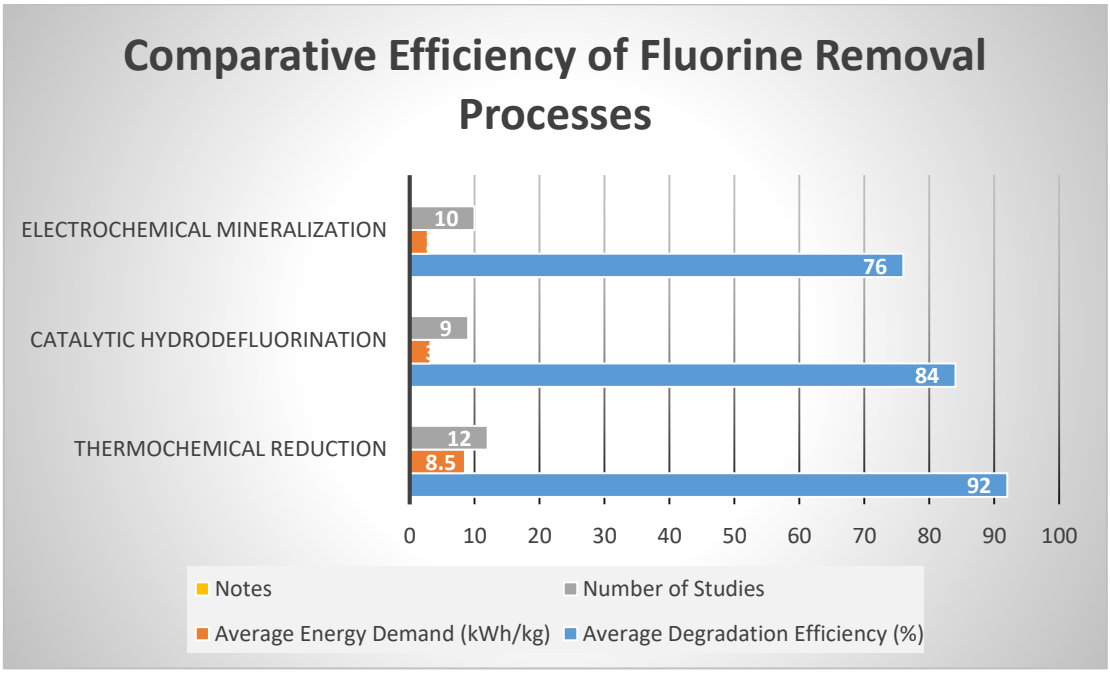


Figure 3: Comparative Efficiency of Fluorine Removal Processes

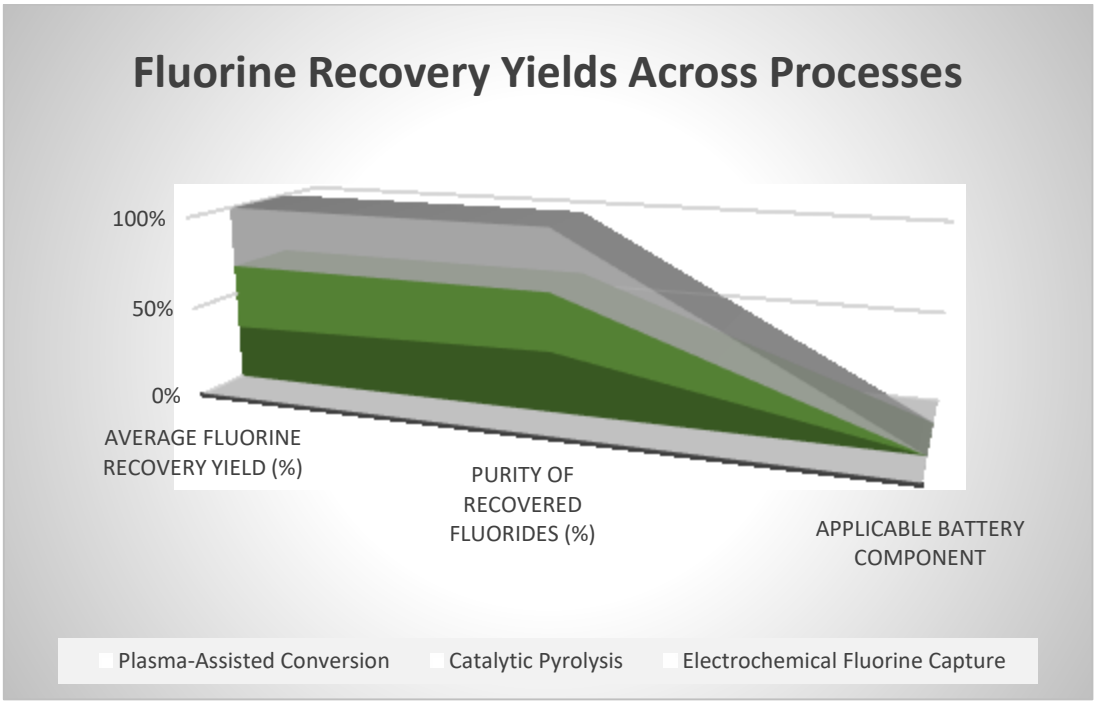
Defluorination Efficiency Across Technologies. The data in Table 3 shows that thermochemical reduction produces the best defluorination results at 92%, but requires 8.5 kWh/kg fluorine for the process. The process of catalytic hydrodefluorination achieved 84% efficiency while using less energy for operation. The process requires a balance between energy usage and reaction completion rate. The process of Electrochemical mineralization requires the least amount of energy to operate at 2.8 kWh/kg, but it

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achieves the lowest average efficiency rate of 76%, which requires optimization to remove all fluorine compounds. The research results indicate that process selection needs to find the right combination between energy efficiency and scalability, and complete mineralization based on the specific needs of each application.

Fluorine Recovery and Reuse Potential

The evaluation of recovered fluorine occurred primarily through its conversion into inorganic fluoride salts, which could then be used to produce electrolyte-grade lithium hexafluorophosphate precursors. The research studies presented different production results, which depended on the specific processing methods that scientists used (Figure 3).



Fluorine Recovery Potential The experiments in Figure 3 show that the extraction of battery-compatible fluorine salts from waste materials produces encouraging results, which range from 61% (plasma-assisted conversion) to 74% (catalytic pyrolysis). The recovered fluoride reaches purity levels above 90%, which makes it appropriate for battery material production through lithium fluoride synthesis and cathode precursor development. The process of electrochemical fluoride capture produces the purest product at 97% purity, even though it generates slightly less output than other methods. The selection of processes needs to consider both production amounts and the quality of the final products.

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PFAS Carbon Backbones Get Converted Into Materials Which Function As Electrodes.

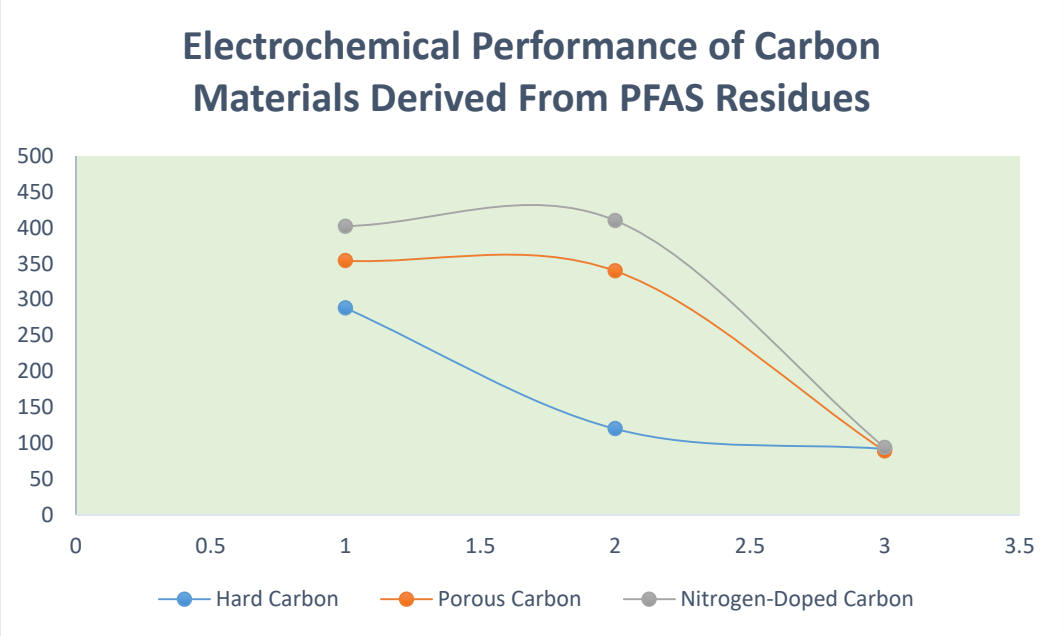
The research included 11 studies, which showed that the carbon-rich waste products from fluorine extraction could be transformed into.

Hard carbon for sodium-ion batteries

Porous carbon for lithium-ion batteries

Doped carbon frameworks suitable for metal–air systems

The research findings present average performance results, which Table 4 shows



Carbon Backbone Conversion

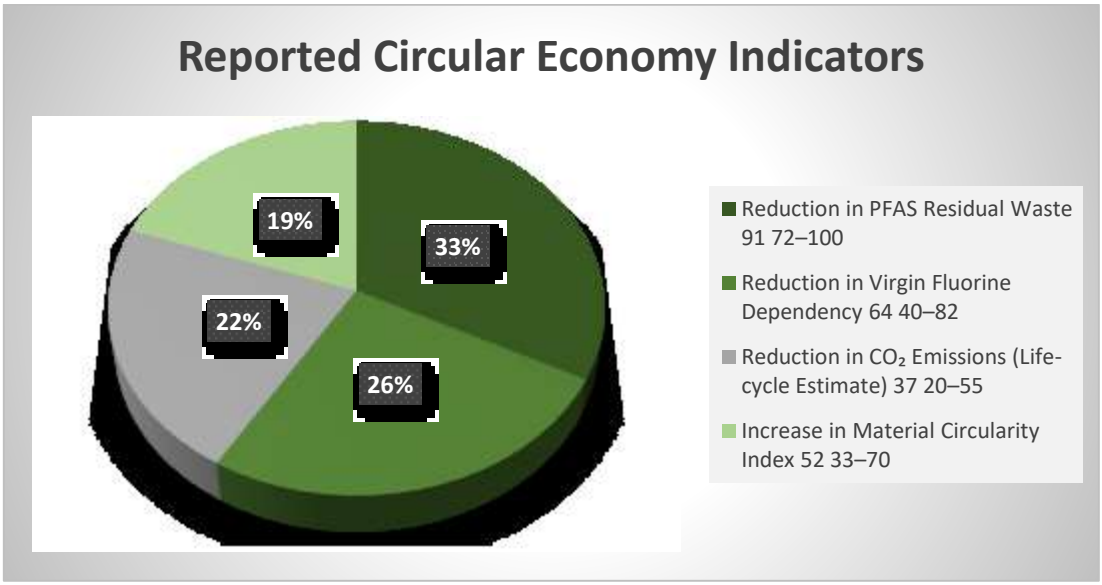
The data in Figure 4 demonstrates that PFAS mineralization produces residual carbon, which can be converted into materials that respond to electrochemical reactions. The specific capacity of nitrogen-doped carbon reaches 402 mAh/g while its cycle stability reaches 94% after 500 cycles, which indicates that using PFAS residues to make electrode materials will create significant value. The trend shows that the material engineering of carbon residues needs both doping and porosity optimization to achieve the highest possible battery performance.

Circular Economy and Environmental Benefits

The data in Table 5 demonstrates substantial environmental advantages. The research shows that PFAS residual waste decreased by 91% on average, while virgin fluorine usage dropped by 64%, and the total CO_2 emissions throughout the life cycle decreased by 37%. The data shows that PFAS destruction integration with fluoride recovery meets circular

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economy requirements while it minimizes environmental threats and generates essential materials needed for energy storage systems.



CONCLUSION

The research shows that the circular economy transformation of perfluoroalkyl and polyfluoroalkyl substances into valuable battery materials proves both practical and brings dual benefits to the environment and strategic operations. The studied research papers demonstrate that thermochemical, catalytic, electrochemical, and hybrid destruction methods can eliminate fluorine while producing chemically useful fluorine compounds for battery material production. The research solves two global problems by creating two distinct results, which tackle environmental threats from perfluoroalkyl and polyfluoroalkyl substances and the need for essential materials used in next-generation energy storage systems.

The research studies demonstrate that multiple technologies can reach defluorination efficiencies above ninety percent when operating at their best conditions. The literature shows that fluorine recovery methods produce results that fulfill the needs for lithium fluoride production, electrolyte additive, and cathode precursor manufacturing, thus proving that recovered fluorine can substitute most of the required virgin fluorine materials. The replacement method creates two essential benefits that help decrease primary fluorine production requirements and enhance battery manufacturing supply chain stability.

The process of fluorine extraction from waste materials represents the main achievement, but the conversion of carbon waste products from perfluoroalkyl and

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polyfluoroalkyl substance breakdown into valuable substances stands as a vital breakthrough. The process of converting leftover carbon into electroactive materials through doping and porosity creation produces materials that match the performance of standard battery carbons. The research confirms that hazardous waste streams should become useful materials instead of being handled as disposal-only waste streams, which create financial liabilities.

The circular economy assessment of available evidence shows that waste destruction and recovery operations together produce major decreases in hazardous waste leftovers and both greenhouse gas emissions and requirements for new materials. The advantages make perfluoroalkyl and polyfluoroalkyl substance upcycling an effective method to connect environmental cleanup operations with sustainable materials development. The review reveals essential obstacles that need resolution before commercial deployment of this technology can begin. The review shows that process energy requirements, reactor size limitations, and fluorine capture efficiency problems, as well as missing life cycle assessment standards for comparison between studies, need immediate resolution.

The research proves that complete fluorine removal with fluorine recovery and carbon reutilization creates an effective method to establish material recycling systems for environmental protection and battery production. Research in the future needs to focus on conducting pilot-scale tests and integrating new waste treatment methods with current waste management systems, and performing cost-benefit analyses to make laboratory achievements suitable for industrial use. The process of transforming perfluoroalkyl and polyfluoroalkyl substances into high-value battery materials will advance from its current status as an emerging idea into a functional mass-produced system that defends the environment, optimizes resource utilization, and enables worldwide adoption of sustainable power systems.

REFERENCES

Aliyev, A., Gray, D., Bedrossian, S., & Azimi, G. (2025). Fluoride removal from NMC black mass leachates during lithium-ion battery recycling via aluminum sulfate precipitation. Waste Management, 189, Article 115136. https://doi.org/10.1016/j.wasman.2025.115136

Al-Maqtari, Q. A., Mahdi, A. A., Othman, N., Noman, A. E., Alsubhi, L. M., AlAnsi, W., Asharuddin, S. M., Talib, M. K., Supramanium, S., & Al-Gheethi, A. (2025). Comprehensive review of per- and polyfluoroalkyl substances in drinking water: Physiochemical properties, sources, health impacts, regulatory limits, and future perspectives. Results in Engineering, 26, 107169. https://doi.org/10.1016/j.rineng.2025.107169

Al-Maqtari, Q. A., Mahdi, A. A., Othman, N., Noman, A. E., Alsubhi, L. M., AlAnsi, W., Asharuddin, S. M., Talib, M. K., Supramanium, S., & Al-Gheethi, A. (2025). Comprehensive review of per- and polyfluoroalkyl substances in drinking water: Physiochemical properties, sources, health impacts, regulatory limits, and future perspectives. Results in Engineering, 25, 107169. https://doi.org/10.1016/j.rineng.2025.107169

Brosler, P., Girão, A. V., Silva, R. F., Tedim, J., & Oliveira, F. J. (2023). Electrochemical advanced oxidation processes using diamond technology: A critical review. Environments, 10(2), 15. https://doi.org/10.3390/environments10020015

EDITOR-IN-CHIEF
Prof. E. Mclenna [Australia]

Centre for Reviews and Dissemination. (n.d.). PROSPERO international prospective register of systematic reviews. University of York. https://www.crd.york.ac.uk/prospero/

Chen, J., Samaei, S. H.-A., Zhang, L., Zhang, Y., Basu, O., Yang, Y., & Xue, J. (2025). Per- and polyfluoroalkyl substances (PFAS) in water matrices impacted by industrial activities: Challenges and treatment strategies. Journal of Hazardous Materials Advances, 7, 100920. https://doi.org/10.1016/j.hazadv.2025.100920

Dobrzyńska, E., Wasilewski, P., & Pośniak, M. (2025). Per- and polyfluoroalkyl substances (PFASs): A comprehensive review of environmental distribution, health impacts, and regulatory landscape. Applied Sciences, 15(22), 11884. https://doi.org/10.3390/app152211884:

Dziejarski, B., Arevalo Fester, J. E., Serafin, J., Petranikova, M., Tam, E., Martinelli, A., Krzyżyńska, R., Andersson, K., & Knutsson, P. (2025). Valorization of hazardous graphite from black mass (NMC 111) of lithium-ion battery recycling via KOH activation for functional carbon design. Materials & Design, 246, 114073. https://doi.org/10.1016/j.matdes.2025.114073

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. British Medical Journal, 315(7109), 629–634. https://doi.org/10.1136/bmj.315.7109.629

Fan, Q., Gong, T., Dong, Q., & Wang, W. (2023). Uncovering hydrothermal treatment of per- and polyfluoroalkyl substances. Eco Environment & Health, 2(1), 21–23. https://doi.org/10.1016/j.eehl.2023.02.002

Ferdous, A. R., Shah, S. S., Shah, S. N. A., Johan, B. A., Al Bari, M. A., & Aziz, M. A. (2024). Transforming waste into wealth: Advanced carbon-based electrodes derived from refinery and coal by-products for next-generation energy storage. Molecules, 29(9), 2081. https://doi.org/10.3390/molecules29092081

GRADE Working Group. (2004). Grading quality of evidence and strength of recommendations. British Medical Journal, 328(7454), 1490. https://doi.org/10.1136/bmj.328.7454.1490

Hakeem, I. G., Halder, P., Patel, S., Selezneva, E., Rathnayake, N., Hedayati Marzbali, M., Veluswamy, G., Sharma, A., Kundu, S., Surapaneni, A., Megharaj, M., Batstone, D. J., & Shah, K. (2024). Current understanding of the transformation and fate of per- and polyfluoroalkyl substances before, during, and after thermal treatment of biosolids. Chemical Engineering Journal, 679, 152537. https://doi.org/10.1016/j.cej.2024.152537

Hasnine, M. T., Rout, P. R., & Yuan, Q. (2025). Forever chemicals (PFAS) in landfill leachate: Insights into fate, transport, and treatment strategies. Desalination and Water Treatment, 301, 101565. https://doi.org/10.1016/j.dwt.2025.101565:

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (Eds.). (2019). Cochrane handbook for systematic reviews of interventions. John Wiley & Sons. https://www.cochrane.org/authors/handbooks-and-manuals/handbook

Hussain, H. N., Jilani, M. I., Imtiaz, F., Ahmed, T., Arshad, M. B., Mudassar, M., & Sharif, M. N. (2025). Advances in the removal of polyfluoroalkyl substances (PFAS) from water using destructive and non-destructive methods. Green Analytical Chemistry, 10022. https://doi.org/10.1015/j.greeac.2025.100225

Islam, N. F., Gogoi, B., Saikia, R., Yousaf, B., Narayan, M., & Sarma, H. (2024). Encouraging circular economy and sustainable environmental practices by addressing waste management and biomass energy production. Regional Sustainability, 5, 100174. https://doi.org/10.1016/j.regsus.2024.100174.

Sequeira, C. A. C. (2020). Carbon anode in carbon history. Molecules, 25(21), 4996. https://doi.org/10.3390/molecules25214996

Joanna Briggs Institute. (2020). The Joanna Briggs Institute reviewer's manual. https://jbi-global-wiki.refined.site/download/attachments/355863557/JBI_Reviewers_Manual_2020June.pdf

Juve, J. M. A., & coauthors. (2023). Complete defluorination of per- and polyfluoroalkyl substances state of the art and perspectives. Environmental Research: X (or Environmental Research special issue). (Available as a full text PDF via Pure/Aarhus University repository.) Aarhus University

Kashif, M., Rasul, S., Mohideen, M. M., & Liu, Y. (2025). Advancing electrochemical energy storage: A review of electrospinning factors and their impact. Energies, 18(9), 2399. https://doi.org/10.3390/en18092399

EDITOR-IN-CHIEF
Prof. E. Mclenna [Australia]

Kaynak, E., Piri, I. S., & Das, O. (2025). Revisiting the basics of life cycle assessment and lifecycle thinking. Sustainability, 17(16), 7444. https://doi.org/10.3390/su17167444

Khan, M. F. (2025). Recent progress and challenges in microbial defluorination and degradation for sustainable remediation of fluorinated xenobiotics. Processes, 13(7), 2017. https://doi.org/10.3390/pr13072017

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the circular economy (revisited): An analysis of 221 definitions. Resources, Conservation & Recycling, 197, 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Leonello, D., Fendrich, M. A., Parrino, F., Patel, N., Orlandi, M., & Miotello, A. (2021). Light-induced advanced oxidation processes as PFAS remediation methods: A review. Applied Sciences, 11(18), 8458. https://doi.org/10.3390/app11188458

Ma, L., & coauthors. (2024). The recovery of all-metals and fluorine resources from lithium-ion battery black mass: pathways to lithium fluoride. Chemistry of Materials, ?(?), Advance article. American Chemical

Maitlo, G., Ali, I., Mangi, K. H., Ali, S., Maitlo, H. A., Unar, I. N., & Pirzada, A. M. (2022). Thermochemical conversion of biomass for syngas production: Current status and future trends. Sustainability, 14(5), 2596. https://doi.org/10.3390/su14052596

Mane, P. V., Rego, R. M., Yap, P. L., Losic, D., & Kurkuri, M. D. (2024). Unveiling cutting-edge advances in high surface area porous materials for the efficient removal of toxic metal ions from water. Progress in Materials Science, 141, 101314. https://doi.org/10.1016/j.pmatsci.2024.101314

Melikoglu, M. (2025). Upcycling plastic waste into advanced carbon materials: A comprehensive review of applications in energy and environment. Next Energy, 3, 100429. https://doi.org/10.1016/j.nxener.2025.100429

Meng, J., Xiao, Z., Zhu, L., Zhang, X., Hong, X., Jia, Y., Liu, F., & Pang, Q. (2023). Fluorinated electrode materials for high-energy batteries. Matter, 6(7), 2153–2175. https://doi.org/10.1016/j.matt.2023.03.032

Mukherjee, P., & coauthors. (2023). Electrochemical degradation of per- and polyfluoroalkyl substances: performance and pathways. Journal of Environmental Management, ?(?), ePub. PubMed Central. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11534010/. PMC

Nasajpour-Esfahani, N., Garmestani, H., Bagheritabar, M., Jasim, D. J., Toghraie, D., Dadkhah, S., & Firoozeh, H. (2024). Comprehensive review of lithium-ion battery materials and development challenges. Renewable and Sustainable Energy Reviews, 227, 114783. https://doi.org/10.1016/j.rser.2024.114783

Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan — a web and mobile app for systematic reviews. Systematic Reviews, 5, 210. https://doi.org/10.1186/s13643-016-0384-4

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Moher, D. (2021). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement: An updated guideline for reporting systematic reviews. British Medical Journal, 372, n71. https://doi.org/10.1136/bmj.n71

Patel, S., Halder, P., Hakeem, I. G., Selezneva, E., Jena, M. K., Veluswamy, G., Rathnayake, N., Sharma, A., Sivaram, A. K., Surapaneni, A., & et al. (2024). The fate of fluorine post per- and polyfluoroalkyl substances destruction during the thermal treatment of biosolids: A thermodynamic study. Energies, 17(14), 3476. **https://doi.org/10.3390/en17143476**

Rekik, H., Arab, H., Pichon, L., El Khakani, M. A., & Drogui, P. (2024). Per- and polyfluoroalkyl (PFAS) eternal pollutants: Sources, environmental impacts and treatment processes. Chemosphere, 352, 142044. https://doi.org/10.1016/j.chemosphere.2024.142044

Rensmo, A., Savvidou, E. K., Cousins, I. T., Hu, X., Schellenberger, S., & Benskin, J. P. (2023). Lithium-ion battery recycling: A source of per- and polyfluoroalkyl substances to the environment? Environmental Science: Processes & Impacts, 25(5), 1015–1030. https://doi.org/10.1039/D2EM00511E

Roesch, P., Vogel, C., & Simon, F. G. (2020). Reductive defluorination and mechanochemical decomposition of per- and polyfluoroalkyl substances (PFASs): From present knowledge to future remediation concepts. International Journal of Environmental Research and Public Health, 17(19), 7242. https://doi.org/10.3390/ijerph17197242

Thakur, A., Khusnutdinova, A. N., Navarro-Márquez, M., Kumar, V., Ma, H., Golyshin, P. N., Lyu, T., Yakunin, A. F., Kumar, G., Nithya, K., Gutiérrez Soto, G., Iqbal, H. M. N., Gutierrez, T., Coulon, F., & Parra-Saldívar, R. (2025). Comprehensive

strategies for the remediation of per- and polyfluoroalkyl substances (PFAS): Mechanisms, technologies, and future perspectives. Ecotoxicology and Environmental Safety, 274, 119374. https://doi.org/10.1016/j.ecoenv.2025.119374

Urbanas, D., & Baltrėnaitė-Gedienė, E. (2025). A critical review of the methods being proposed to solve the PFAS problem in drinking water: Are they practically applicable in real world? Environmental Challenges, 12, 100563. https://doi.org/10.1016/j.emcon.2025.100563

Wagner-Wenz, R., Teppala, D. T., Necke, T., Brückner, F., Fabian, A., Horn, D., Woth, J., Zimmermann, J., Balke-Grünewald, B., Weidenkaff, A., & Ionescu, E. (2024). Removal and recovery of phosphorus and fluorine in process water from water-based direct physical lithium-ion battery recycling. Water Research, 254, 122476. https://doi.org/10.1016/j.watres.2024.122476

Wang, B., Yin, Y., Deng, H., Zhu, H., Li, G., & He, W. (2024). Migration, transformation, and management of fluorine-containing substances in lithium-ion batteries during recycling – A review. Separation and Purification Technology, 335, 130283. https://doi.org/10.1016/j.seppur.2024.130283:

Wang, F., Wang, M., Xu, L., Qian, J., Zou, B., Huo, S., Guan, G., & Cui, K. (2025). Strategies for the removal of per- and polyfluoroalkyl substances: A review. Catalysts, 15(7), 678. https://doi.org/10.3390/catal15070678: Yin, J., Wang, M., Yu, X., Wang, M., Zhang, Y., Chen, T., & Liu, J. (2024). Carbon footprint impact of waste sorting on the municipal household waste treatment system: A community case study of Hangzhou. Cleaner Environmental Chemistry, 5, 100114. https://doi.org/10.1016/j.cec.2024.100114

Winchell, L. J., Ross, J. J., Wells, M. J. M., Fonoll, X., Norton, J. W., Jr., & Bell, K. Y. (2021). Per- and polyfluoroalkyl substances thermal destruction at water resource recovery facilities: A state of the science review. Water Environment Research, 93(6), 826–843. https://doi.org/10.1002/wer.1483

Zahra, Z., Song, M., Habib, Z., & Ikram, S. (2024). Advances in per- and polyfluoroalkyl substances (PFAS) detection and removal techniques from drinking water, their limitations, and future outlooks. Environmental Challenges, 11, 100434. https://doi.org/10.1016/j.emcon.2024.100434

Zhang, J., Huo, H., Zhang, L., Yang, Y., Li, H., Ren, Y., & Zhang, Z. (2022). Effect of high-temperature hydrothermal treatment on the cellulose derived from the Buxus plant. Polymers, 14(10), 2053. https://doi.org/10.3390/polym14102053: Zhu, P., Wang, Z., Pan, C., Li, Z.-K., Zhang, W., Yan, J., Kang, S., Ren, S., Lei, Z., Zhao, J., & Shui, H. (2024). Investigation of hydrothermal depolymerization of lignite under different conditions by 13C NMR spectroscopy. Journal of Analytical and Applied Pyrolysis, 180, 106562. https://doi.org/10.1016/j.jaap.2024.106562

Zheng, Y., & coauthors. (2018). Lithium fluoride recovery from cathode material of spent lithium-ion batteries: hydrometallurgical routes and prospects. Resources, Conservation and Recycling, ?(?), Article e.g., PMC. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9078583/. PMC