



Rapid evidence assessment of PFAS incineration and alternative remediation methods

Chief Scientist Group report

September 2025

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List of abbreviations

Abbreviation	Definition
5:3 FTCA	5:3 Fluorotelomer carboxylic acid
6:2 FTOH	6:2 Fluorotelomer alcohol
AFFF	Aqueous Film Forming Foam
CAC	Colloidal Activated Carbon
CHP	Catalysed Hydrogen Peroxide Propagation
COMAH	Control of Major Accident Hazards
DE	Destruction Efficiency
DRE	Destruction Removal Efficiency
Defra	Department for Environment Food and Rural Affairs
DoD	US Department of Defense
EA	Environment Agency
ECHA	European Chemicals Agency
EO	Electrochemical Oxidation
EU	European Union
European Economic Area	EEA
F3	Fluorine free foam
FASA	Perfluoroalkane sulfonamide

Abbreviation	Definition
FFF	Firefighting Foams
FTSA/FTS	Fluorotelomer sulfonic acid
GAC	Granular Activated Carbon
GDP	Gross Domestic Product
HALT	Hydrothermal Alkaline Treatment
HSE	Health and Safety Executive
HTI	High Temperature Incineration
HWI	Hazardous Waste Incinerators
ITRC	Interstate Technology & Regulatory Council
IX	Ion Exchange
LC-MS/MS	Liquid chromatography-tandem mass spectrometry
MWI	Municipal waste Incinerators
OECD	Organisation for Economic Co-operation and Development
OTM	Other Test Method
PFAAs	Perfluoroalkyl Acids
PFAS	Per- and polyfluoroalkyl substances
PFBA	Perfluorobutanoic Acid
PFBS	Perfluorobutane sulfonic acid

Abbreviation	Definition
PFCA	Perfluoroalkyl carboxylate, Perfluoroalkyl carboxylic acid
PFCs	Perfluorocarbons
PFECA	Per- and polyfluoroether carboxylic acids
PFHxA	Perfluorohexanoic Acid
PFHxS	Perfluorohexanesulfonic Acid
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane sulfonate
PFAAs	Perfluorooctanesulfonamide
PFPeA	Perfluoropentanoic acid
PFSA	Perfluoroalkyl sulfonate, Perfluoroalkane sulfonic acid
PICO	Problem, Intervention, Comparison, Outcome
PICs	Products of Incomplete Combustion
POPs	Persistent Organic Pollutants
PTFE	Polytetrafluoroethylene
RMOA	Regulatory Management Option Analysis
RO	Reverse Osmosis
SCWO	Supercritical Water Oxidation
TFA	Trifluoroacetic Acid

Abbreviation	Definition
TOP	Total oxidizable precursor
UK REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
UNEP	United Nations Environment Program
USA	United States of America
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
WWTP	Wastewater treatment plants
ZVI	Zero-Valent Iron
mg/L	milligrams per litre
µg/L	micrograms per litre
ng/L	nanograms per litre
°C	Degrees Celsius

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Executive Summary

Per and polyfluoroalkyl substances (PFAS) are a group of thousands of synthetic fluorinated organic chemicals. They have been widely used in products and industrial processes since the 1950s for their stability and resistance to water and oil. Their extreme persistence and widespread presence in the environment make them technically difficult and costly to remediate, drawing increasing global regulatory attention.

High temperature incineration (HTI) is currently the only commercially viable method for large scale PFAS destruction, particularly for PFAS-containing firefighting foams, which are a notable source of environmental emissions. However, due to high energy demands, sustainability concerns, and the need for precise operating conditions, there is growing interest in alternative remediation technologies. At the same time, proposed regulatory restrictions on PFAS firefighting foams are expected to increase demand for HTI and accelerate the need for alternative solutions. Emerging and existing alternative technologies vary in scalability, effectiveness, and environmental impact, and require comparative evaluation to support sustainable and effective PFAS waste management.

In this rapid evidence review we collate knowledge on HTI destruction of PFAS containing waste. The review also considers alternative PFAS remediation technologies for their practical feasibility, treatment performance and environmental effects. It describes knowledge in 3 areas: (i) the operational conditions required for consistent and near complete PFAS mineralisation. (ii) the formation and environmental fate of products of incomplete combustion (PICs) during HTI and (iii) the effectiveness of current emissions and residue monitoring practices. The review aims to build a strong evidence base that will support the Environment Agency, Defra and others in shaping risk prevention strategies; provide practical insights for industry stakeholders and inform future regulatory strategy, operational decision-making, and infrastructure planning, in response to tightening UK and international restrictions on PFAS use and disposal.

The effectiveness of incineration depends on PFAS concentration, chemical structure, waste type, and operating conditions. HTI can achieve near-complete mineralisation and PFAS destruction efficiencies of >99.99% for PFAS containing firefighting foams, when operated at 1,100°C, with a 2–3 second residence time in the secondary combustion chamber, sufficient turbulence, and properly balanced stoichiometry (waste, fuel, oxygen, and gas-phase components). Suboptimal conditions, such as lower temperatures, poorly mixed oxygen deficient zones, shorter residence times and the absence of hydrogen sources, may lead to the formation of products of incomplete combustion (PICs). Some of these PICs have high global warming potentials and limited measurements have been made at real world incinerator facilities globally.

The influence of additional process conditions, such as the gas environment (inert vs oxidative), water vapour, flame radicals and additives or catalysts such as calcium and aluminium on PFAS thermal decomposition requires further study. Residue monitoring approaches are limited. Current methods typically capture only a subset of PFAS and may

miss key by-products. Without standardised sampling procedures and consistent analytical techniques, comparison of emissions data and destruction efficiency assessments between studies is difficult. The use of multiple PIC surrogates alongside fluorine mass balance tracking may offer a more accurate picture of destruction efficiency. However, the diversity of PFAS, their typically low concentrations, high background fluoride, precursor presence, and possible fluoride precipitation can hinder efforts to achieve a complete fluorine mass balance.

Most studies to date have been conducted under laboratory conditions, failing to replicate real world waste variability. Evaluating real world treatment facilities across different waste types could provide insight into how operational conditions affect both destruction and PIC formation, helping validate or refine current guidelines. Computational studies could further support this by modelling PFAS decomposition pathways and PIC formation under high temperature oxidising conditions.

PFAS source reduction remains essential to reducing reliance on incineration and other remediation methods. Understanding PFAS levels in municipal waste streams and assessing the destruction capabilities of municipal waste and sewage sludge incinerators, many of which operate at lower temperatures, is equally important, as these facilities may already be treating PFAS without full recognition of the implications.

Improved incinerator design to ensure consistent optimal conditions, along with enhanced flue gas treatment systems, may be required to more effectively capture volatile PFAS and degradation products. Additionally, the environmental and climate impacts of PFAS remediation must be considered, particularly given the energy-intensive nature of incineration. Climate resilient, low emission alternatives should be further explored alongside improvements to existing technologies.

Emerging destructive technologies, including mechanochemical degradation, hydrothermal alkaline treatment, sonolysis, plasma treatment, electrochemical oxidation, supercritical water oxidation, pyrolysis, and gasification, show good potential for the effective destruction of PFAS across a range of waste streams. However, there is currently no silver bullet. These methods require ongoing development, real world testing, and long-term performance data to demonstrate their scalability and environmental safety.

Adsorptive methods such as granular activated carbon, ion exchange, and membrane filtration are widely used to remove PFAS from water and other media. Separation methods like foam fractionation, flocculation and soil washing are also used to extract and concentrate PFAS into smaller volumes of waste. While established and effective for treating localised contamination, these approaches generate PFAS rich residuals that require careful management to avoid environmental re-release. They are also generally less effective for the more hydrophilic short-chain PFAS. Combining these techniques with destructive technologies into integrated treatment trains may offer a more scalable, cost-effective, and sustainable approach to PFAS management. Targeted solutions based on waste type and contamination levels are promising, though long-term validation is needed.

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1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a broad and diverse class of synthetic organofluorine chemicals ([ECHA, 2023](#); [OECD 2018](#); [US EPA, 2022c](#)). Since the 1950s, they have been used in various industrial sectors and consumer products (including certain firefighting foams, drugs, defence, pesticides, textiles, electronics, lubricants, food packaging, vehicles, gaskets, repellents, sunscreens, cosmetics and many more) for their chemical and thermal resistance, low surface tension, and water and oil repellent properties ([Buck et al., 2021](#); [Glüge et al., 2020](#); [Inoue et al., 2020](#)). These desirable properties result from the carbon–fluorine (C–F) bond, which is the strongest single bond in organic chemistry ([Buck et al., 2011](#); [Kissa, 2001](#); [Leung et al., 2022](#); [O’Hagan, 2008](#)).

There is no single, globally adopted definition of PFAS for human health or environmental regulation ([HSE, 2023](#)). The Organisation for Economic Co-operation and Development (OECD) 2021 definition, which classifies any chemical with at least one fully fluorinated methyl (-CF₃) or methylene (-CF₂-) group as a PFAS (with a few noted exceptions), is now widely used in science and policy ([OECD, 2021](#)). This broad structural definition is useful for identification ([PubChem, 2024](#); [Schymanski et al., 2023](#); [Z. Wang et al., 2021](#)), but does not account for the various physical, chemical, and ecotoxicological differences between these substances. As a result, there’s a growing drive to develop grouping strategies and mixture-based risk assessments to more effectively manage PFAS ([Cousins et al., 2022b](#); [Zeilmaker et al., 2018](#)).

Although PFAS and their degradation products are diverse, they generally share a defining trait of extreme environmental persistence ([Cousins et al., 2020](#)). The high mobility of many PFAS, coupled with their environmental persistence, enables their detection in all environmental compartments across the globe, including remote regions ([Ackerman Grunfeld et al., 2024](#); [Ankley et al., 2021](#); [Armitage et al., 2006](#); [Cousins et al., 2022](#); [Muir and Miaz, 2021](#); [Xie and Kallenborn et al., 2023](#)), which demonstrates their widespread dispersion potential ([Faust, 2023](#); [Kurwadkar et al., 2022](#); [Saifur and Gardner 2021](#); [Sha et al., 2024](#)). The continuous cycling of PFAS increases environmental contamination while certain PFAS also bioaccumulate, raising uncertainties about long-term exposure impacts on ecosystems and human health ([Brunn et al., 2023](#); [Pelch et al., 2019](#); [HSE, 2023](#)).

Regulatory efforts have primarily focused on non-polymer perfluorinated PFAS and their precursors ([Environment Agency, 2021](#); [Henry et al., 2018](#)), especially perfluoroalkyl acids (PFAAs) such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), due to their persistence and widespread presence in the environment. These substances were commonly used and also often appear as terminal degradation products of other PFAS through environmental or biological processes ([Ahrens et al., 2014](#); [Liu and Mejia Avendaño, 2013](#)). Hence, many PFAS are considered to be PFAA precursors ([Matsukami et al., 2024](#); [OECD, 2022](#); [Russell et al., 2008](#); [Vestergren et al., 2008](#); [Wallington et al., 2006](#)). PFAAs are highly mobile and have been detected in drinking water and other sensitive environments. Structurally, they consist of a fully fluorinated, hydrophobic carbon

chain attached to a hydrophilic functional group, forming a hydrophobic tail and hydrophilic head, as shown in **Figure 1** ([Kjølholt et al., 2015](#); [Panieri et al., 2022](#)).

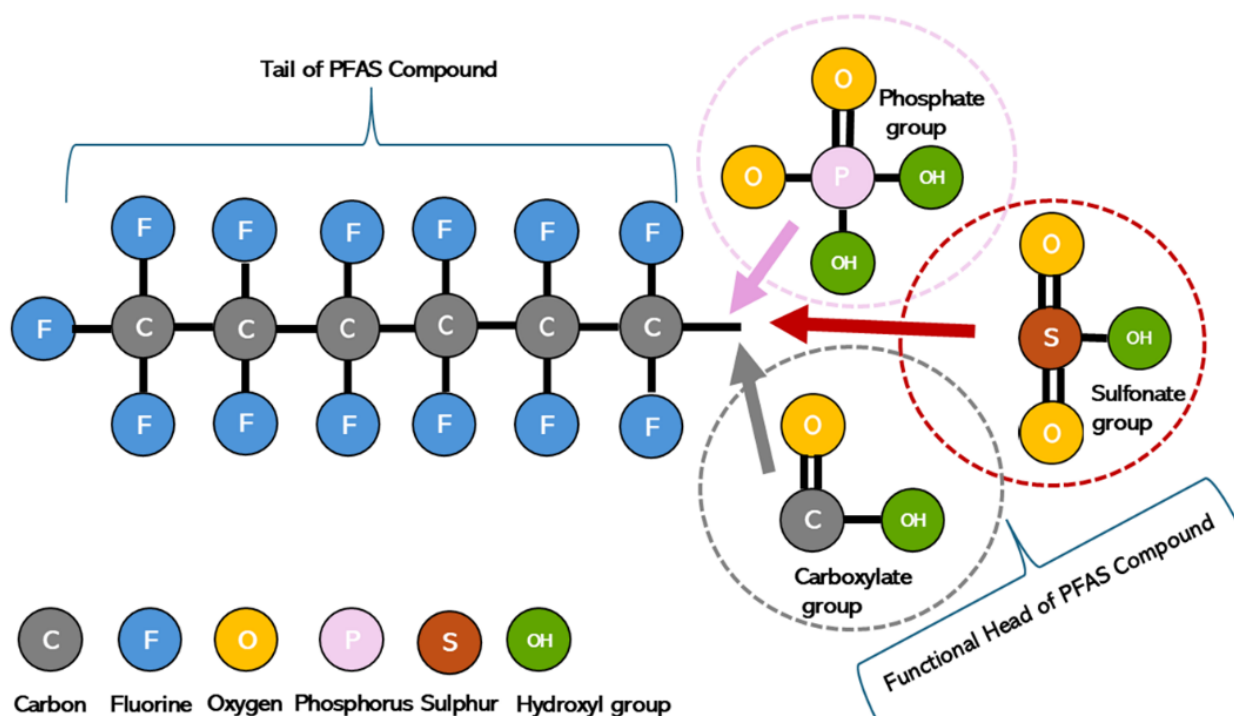


Figure 1. General structure of non-polymer, perfluorinated PFAS. Variations in chain length, degree of fluorination, and type of functional group create a wide diversity of PFAS compounds.

Researchers have compiled a growing database of studies on the health effects of different PFAS ([PFAS-Tox](#)). However, of the thousands of PFAS, fewer than 50 have robust toxicological data to fully assess their risks ([ECCC and Health Canada, 2024](#)). Among them, PFOA and PFOS, are the most widely studied ([COT, 2022](#)). Their exposure has been linked to certain cancers, developmental and reproductive effects, immune suppression, thyroid disruption, and impacts on liver and kidney function ([ATSDR, 2021](#); [Fenton et al., 2021](#); [Kwiatkowski et al., 2020](#); [Mastrantonio et al., 2018](#); [Steenland et al., 2020](#)). These substances are readily absorbed through the gastrointestinal tract following ingestion, and tend to accumulate in the blood, liver, and kidneys, persisting in the body for years by binding to serum albumin and other proteins ([Li et al., 2018](#); [Weise et al., 2022](#); [Ng and Hungerbuhler., 2014](#)). Research suggests they can also transfer to fetuses through the placenta and to infants through breastfeeding ([De Silva et al., 2021](#); [McAdam and Bell., 2023](#); [Post et al., 2012](#)). Human exposure to PFAS mixtures may also contribute to cumulative effects ([Bil et al. 2023](#)). However, limited research exists on how different levels of exposure may lead to different health effects and their respective severity. Concerns also exist about using current human epidemiology studies to derive health-based criteria, due to study quality and the clinical significance of select critical effects, highlighting the need for further studies to determine cause and effect relationships ([Anderson et al., 2022](#); [Gustavsson et al., 2023](#); [Environment analyst 2025](#)).

Even with current restrictions, long-chain PFAAs continue to bioaccumulate and biomagnify in UK wildlife, including fish, otters, birds, and marine mammals ([Androulakakis et al., 2021](#); [Chen et al., 2021](#); [Fernandes et al., 2018](#); [Law et al., 2008](#); [Environment Agency, 2019](#); [Environment Agency, 2024](#); [O'Rourke et al., 2024](#); [Pereira et al., 2021](#)). Some studies indicate similar ecotoxicological effects to those found in human studies ([Andrews et al., 2023](#); [Death et al., 2021](#); [Feng et al., 2015](#)), though results are complicated by species specific differences in exposure, elimination, and contamination levels ([Bangma et al., 2022](#)). In terrestrial ecosystems, certain PFAS may impair protein synthesis and photosynthesis, increase soil pH, reduce soil respiration, disrupt microbial communities, alter nutrient cycling, and accumulate in crops. However, research on the impacts of PFAS on plants remains limited ([Ghisi et al., 2019](#); [Li et al., 2022](#); [Xu et al., 2023](#); [Blaine et al., 2014](#); [Costello and Lee, 2020](#); [Felizeter et al., 2020](#); [Knight et al., 2021](#); [T.-T. Wang et al., 2020](#)). Some regulated PFAS show declining trends in certain species and locations ([De Silva et al., 2021](#); [Muir and Miaz, 2021](#); [Environment Agency, 2023](#)), however, variability remains. Meanwhile, increasing concentrations of emerging short chain PFAS are being seen, likely due to their use as replacements for regulated long chain PFAS ([Manojkumar et al., 2023](#)). While most of these replacement PFAS do not bioaccumulate to the same degree, they are just as persistent and often more water soluble and mobile. Preliminary evidence also suggests that some emerging short chain PFAS may also pose significant health risks ([Brendel et al., 2018](#); [Sunderland et al., 2019](#)).

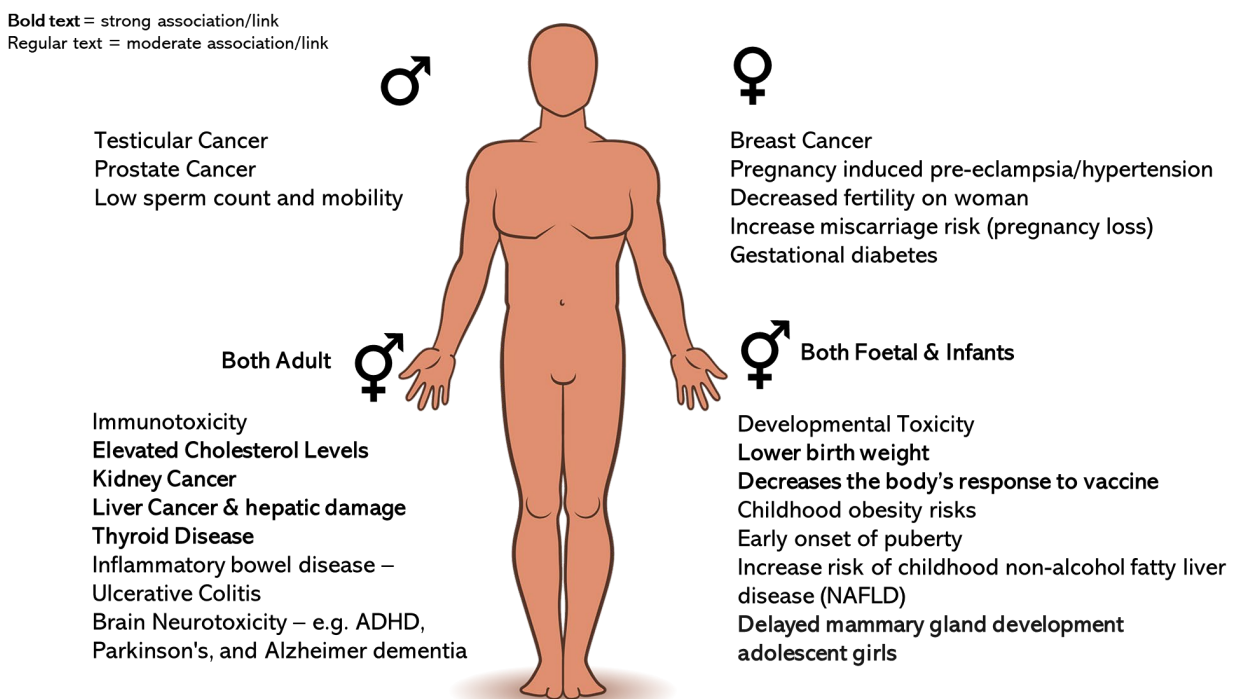


Figure 2. Effects of **certain** PFAS on human health. Modified and redrawn from [Brunn et al., \(2023\)](#) and the [European Environment Agency \(2019\)](#)

PFAS emissions occur throughout their entire lifecycle, from production, storage and use, through to disposal. Industrial processes that produce, process or use PFAS ([Galloway et](#)

al., 2020; Gebbink and Van Leeuwen, 2020; Mok et al., 2023; Pancras et al., 2024) along with historical and ongoing firefighting foam use at fire stations, military sites, airports, refineries and COMAH sites represent major emission sources (Anderson et al., 2016; Barzen-Hanson and Field, 2015; Douglas et al., 2023; Lang et al., 2022; Reinikainen et al., 2022). Waste management facilities including landfills (historic and permitted), wastewater treatment plants (WWTP) and some incinerators, also contribute to PFAS environmental emissions (Arvaniti et al., 2014; Campo et al., 2014; Fuertes et al., 2017; Lenka et al., 2021; Martin et al., 2023; Ross et al., 2018; Schaefer et al., 2023; Solo-Gabriele et al., 2020; B. Wang et al., 2020).

Diffuse sources from professional uses and consumer products can also contribute to overall environmental load. PFAS are released through wear, washing and improper disposal, often entering the environment via runoff and wastewater treatment facilities (Environment Agency, 2021; Dewapriya et al., 2023; Reinhart et al., 2023). Human exposure primarily occurs through the ingestion of contaminated drinking water and food as well as inhalation of indoor air, and contact with contaminated materials (EFSA, 2020, 2021; 2024; Sunderland et al., 2019; Goosey and Harrad, 2012). Currently, only a relatively small number of PFAS are subject to regulatory controls to manage risk to the environment and human health. The majority remain unregulated, potentially allowing them to enter waste streams, contaminate recycled materials, and increase the potential for occupational exposure (Garg et al., 2020; Ng et al., 2021).

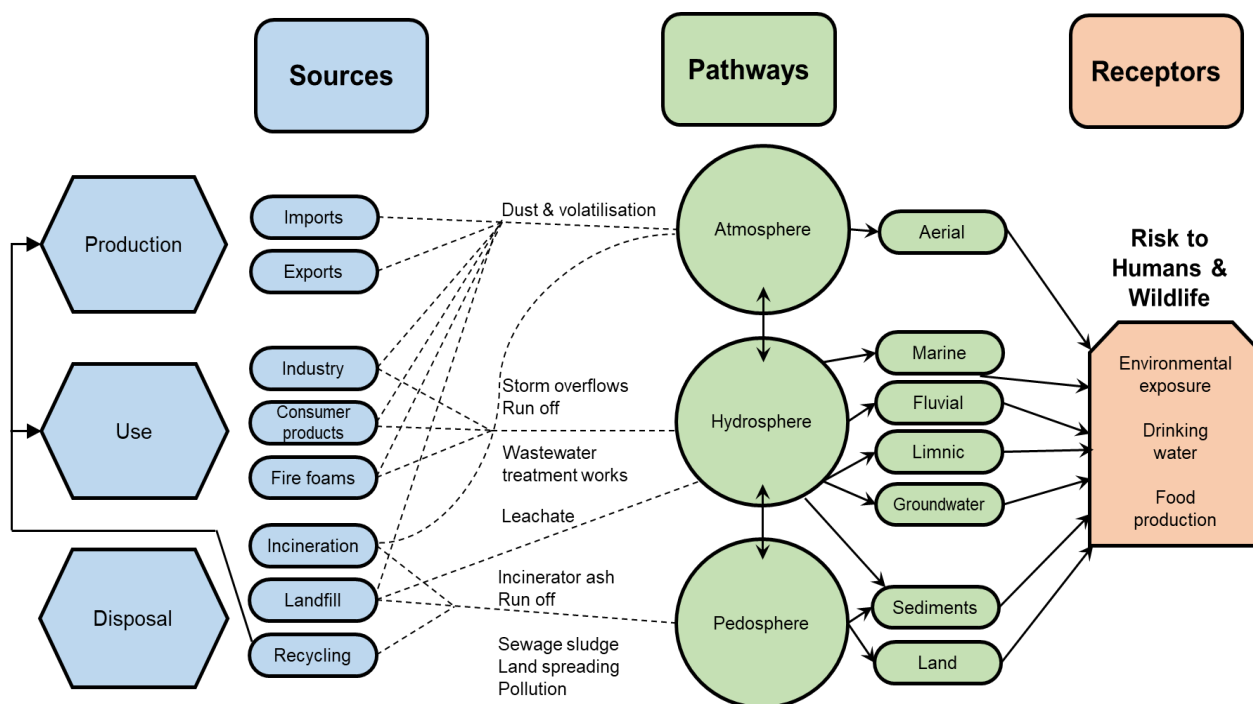


Figure 3. Source, Pathway, Receptor analysis of PFAS contamination. This framework is used to trace how pollutants originate, move through the environment, and ultimately reach and affect receptors (James et al., 2024).

Due to their extreme persistence, PFAS can remain in the environment for an extended period. Across the European Economic Area (EEA), the total number of sites emitting PFAS in some quantity could be in the order of 100,000 ([Goldenman et al., 2019](#)). More recently, an independent group called the Forever Pollution Project reported nearly 23,000 sites across Europe with PFAS contamination above 10 nanograms per litre, based on environmental sampling. In addition, a further 21,500 sites are suspected to be contaminated due to past or current industrial activities ([Horel et al., 2023](#)). There is an estimated 2,900 to 10,200 high risk sites in England. While current estimates of PFAS remediation costs remain uncertain, due to differences in site types and the remediation methods applied, the projected remediation costs for these sites in England range between £31 billion and £121 billion ([Jacobs, 2023](#)). Meanwhile, PFAS related healthcare costs across the EEA are estimated at €52–84 billion annually ([Cordner et al., 2021](#); [Goldenman et al., 2019](#)). Remediating contaminated sites can reduce exposure by targeting key point sources. However, without upstream source controls on PFAS production and use, long-term reliance on environmental remediation is unlikely to be effective due to high costs and the persistence of PFAS, which are resistant to current remediation methods ([Ling 2024](#), [Ling et al., 2025b](#)).

2. Project Rationale

The growing amount of PFAS waste, which includes end of life products, manufacturing residues, adsorbents and contaminated soil or wastewater creates regulatory challenges and may lead to secondary emission sources ([Longendyke et al., 2022](#)). Historically, permits for waste management facilities have included very few specific conditions targeting the destruction of PFAS. However, regulatory controls are evolving, and there is a growing focus on PFAS rich-waste streams that require effective treatment.

PFAS waste is primarily managed through landfilling, wastewater treatment, and incineration. However, except for high temperature incineration these methods do not ensure complete destruction. As a result, PFAS and their precursors have the potential to enter the environment via several pathways (**Figure 3**). In WWTP, PFAS may be discharged to surface and ground waters via effluent or transferred to soils through the application of biosolids, while volatile PFAS may also be released to air with the potential for long-range transport ([HSE, 2025](#); [Lenka et al., 2021](#)). Additional release routes include landfill leachate and residues from incineration, such as ash and atmospheric emissions. The overall volume of PFAS entering these systems remains unknown, limiting the development of reliable emission factors ([Nicholson et al., 2018](#); [Stoiber et al., 2020](#)).

High temperature incineration (HTI) is currently the most implemented method to destroy PFAS contaminated media or waste, specifically stockpiled firefighting foams, and has been widely implemented in the USA and Europe ([Kovacs et al., 2025](#)), offering a route to minimise long term contamination ([Block et al., 2015](#)). HTI typically requires no separation or pretreatment of PFAS and is conducted at hazardous waste incinerators (HWIs) in England, which operate above $\sim 980^{\circ}\text{C}$ with excess oxygen and mineralise (complete defluorination) PFAS into carbon dioxide (CO_2), water (H_2O) hydrogen fluoride (HF) and or sulphur oxides (SO_x) ([Altarawneh et al., 2022](#); [Brunn et al., 2023](#); [Shields et al., 2023](#)).

However, PFAS, particularly the $-\text{CF}_2-$ moieties are extremely thermally stable, making their destruction energy intensive. If temperature, residence time, oxygen or turbulence in the incinerator is inadequate, incomplete combustion may occur. This can lead to the formation of ultra-short-chain (C_1 – C_3) products of incomplete combustion (PICs), such as CF_4 , CHF_3 , C_2F_6 , C_2F_4 and C_3F_6 , many of which are greenhouse gases ([Davies et al., 2024](#); [ECHA, 2023](#); [Stoiber et al., 2020](#)). Parent PFAS substances and longer-chain fluorinated compounds may also survive the process among other short chain PFAS, which can be released in small amounts into the atmosphere or retained in ash which may be landfilled or repurposed. Additionally, there is uncertainty regarding the fate of PFAS in liquid waste streams from incineration as the high temperatures required may result in loss of PFAS through steam discharge from the stack ([Ross, 2020](#)). While much of this evidence comes from international research, similar uncertainties apply to PFAS incineration practices in England.

In England, meeting the operational conditions needed to effectively destroy PFAS often requires running incinerators at the upper limits of what they are typically designed to handle. Adjustments for PFAS specific waste such as elevated temperatures and extended residence times are uncommon. This is partly because PFAS can often enter facilities unknowingly through mixed waste streams, making it difficult to track and optimise destruction efficiency. As a result, current monitoring of flue gas, ash, and residue may not always capture the full range of PFAS and PICs. The literature also reports conflicting and limited findings on the efficiency of PFAS thermal treatment, highlighting the complexity of incineration chemistry, variations in operating conditions, and the incomplete understanding and identification of PICs.

These limitations have led to additional regulatory controls by environmental agencies globally. In the USA, the 2020 National Defense Authorization Act mandated a phase out of PFAS based foams by October 2024 ([Miller, 2024](#)). Due to concerns over limited real-world data and unknown by-products, the Department of Defense (DoD) issued a temporary moratorium in April 2022, suspending the incineration of PFAS containing materials, including firefighting foam ([US DoD, 2023](#); [Crunnden, 2022](#); [GhD, 2023](#); [Koban and Pfluger, 2023](#)). The moratorium will remain in place until the DoD issues updated guidance aligned with the US EPA's interim report. Regarding incineration, the interim report concludes that "*thermal treatment units operating under certain conditions are more effective at destroying PFAS and minimizing releases or exposures*" but also highlights that key uncertainties remain and more research is needed ([US EPA, 2024f](#); [US EPA, 2024](#)). It recommends further testing using validated methods (OTM-45 and 50) to assess PICs emissions.

The European Chemicals Agency (ECHA), in its proposed Annex 15 report, similarly noted that emissions from waste incineration are poorly studied and that PFAS destruction efficiency depends heavily on operational conditions ([ECHA, 2023](#)). ECHA also considered that PFAS destruction efficiency from waste incineration may not always be 100% and assumes an emission factor of <1%, with residual PFAS released to air or retained in bottom/fly ash ([ECHA, 2023b](#); [US EPA, 2024](#); [Stoiber et al., 2020](#)).

Regulatory changes in England are accelerating a shift in PFAS waste management. The use of PFOS and perfluorohexanesulfonic acid (PFHxS) are banned in firefighting foams under the Stockholm Convention, implemented through [EU Regulation 2019/1021](#). A ban on PFOA, its salts and PFOA-related compounds, in firefighting foams took effect in July 2025. As a result, affected foams must be destroyed or irreversibly transformed in line with Article 7 of the POPs Regulations ([Gov.uk, 2025](#)), typically via HTI, to ensure they cannot be reused, recycled, or recovered. Enforcement falls under the [Persistent Organic Pollutants Regulations 2007 SI 3106](#), with the Environment Agency responsible for compliance in England. Additional restrictions on long-chain PFAAs are currently under review. Separate to the UK POPs Regulations, in Summer 2025 the Health and Safety Executive (HSE) published a UK REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) Annex 15 restriction dossier, assessing possible restrictions regarding the use and disposal of PFAS containing firefighting foams ([HSE, 2025](#)).

Given these ongoing developments, reliance on HTI and other remediation technologies for the destruction of PFAS is expected to grow. It is crucial to understand the associated risks and determine to what degree current incineration infrastructure can reliably achieve PFAS mineralisation. This includes identifying operational conditions for near or complete destruction and evaluating alternative technologies based on their feasibility, environmental footprint, and cost effectiveness.

2.1 Aim

The aim of this project is to conduct a rapid evidence review of HTI for the destruction of PFAS containing waste, focusing on known concentrated sources such as firefighting foams (FFF). The review describes knowledge in three areas:

- The operational conditions required for consistent and complete PFAS mineralisation.
- The formation and environmental fate of PICs during HTI.
- The effectiveness of current emissions monitoring practices.

The review also compares HTI with emerging PFAS remediation technologies in terms of practical feasibility, treatment performance and environmental effects. The review aims to build a strong evidence base that will:

- Provide practical insights for industry stakeholders.
- Support Defra, the Environment Agency, and others in shaping risk prevention strategies.
- Inform regulatory strategy, operational decision-making, and infrastructure planning, in response to tightening UK and international restrictions on PFAS use and disposal.

By improving our understanding of HTI as well as alternative remediation methods, this evidence review contributes to the development of sustainable PFAS management approaches. It also aims to answer two research questions:

- **Primary Question:** What are the optimal operational conditions required for the effective destruction of PFAS firefighting foams through incineration?
- **Secondary Question:** How do alternative disposal and remediation methods, including incineration, compare in terms of effectiveness, feasibility, and environmental impacts?

2.2 Methodology and Approach

This rapid evidence assessment combines elements of a quick scoping review and systematic approaches to ensure rigour, relevance, and reproducibility. Following

guidance from [Collins et al. \(2015\)](#) and the PSALSAR (Protocol, Search Appraisal, Synthesis, Analysis, Report) frameworks, the approach aims to reduce bias and focus on key evidence, hence enabling faster delivery than traditional systematic reviews while remaining detailed and ensuring reproducibility ([Whaley et al., 2016](#); [Munafò et al., 2017](#)). A multidisciplinary steering group defined the scope and research questions using the PICO framework (Problem, Intervention, Comparison, Outcome), which guided the formulation of three distinct research themes aligned with the review's primary and secondary questions.

- **Optimising Operational Conditions for PFAS Incineration** – What temperature, residence time and other conditions are needed to destroy PFAS effectively and form minimal PICs?
- **Comparative Analysis of PFAS Remediation Methods** – Assess the effectiveness, compliance and sustainability of different PFAS disposal methods, with focus on incineration.
- **Economic and Environmental Impact Assessment** – Assess the costs, environmental impacts and risks of PFAS disposal approaches to support the safe, sustainable management of PFAS.

To analyse trends and associations, literature from Scopus was processed with VOSviewer software (Version 16.18, 2022) ([Van Eck and Waltman, 2010](#)), generating network maps of keywords, references, institutions, and authors. These were qualitatively assessed to further understand PFAS incineration and remediation. Details on the search strategy, question development, Boolean searches, filtering, and evaluation are provided in [Appendices A–E](#). However, it is worth noting that this field is complex and is rapidly evolving, therefore, updates may be needed as new evidence emerges.

3. Incineration of PFAS: Process, Challenges and Policy

3.1 Introduction to Incineration

Incineration is a well-established thermal treatment process that is used to treat hazardous and non-hazardous wastes. The process involves combusting waste at high temperatures in the presence of excess oxygen/air to reduce its volume and destroy contaminants. Incinerators are furnaces that burn waste under controlled conditions within a combustion chamber ([US EPA, 2021](#)). Several types of incinerators exist, but not all are certified for PFAS destruction. Each has specific configurations designed for different waste streams and treatment objectives ([US EPA, 2024](#)). In the UK, the tonnage of all types of waste incinerated nearly tripled between 2010 and 2020 ([Smith and Bolton, 2025](#)).

High-temperature incineration (HTI), which is typically carried out in hazardous waste incinerators (HWIs) in England, can be used to treat PFAS in contaminated solid, liquids, and gases ([Wang et al., 2022](#)). Including, soils, water, spent adsorbents, biosolids, textiles, leachate, carpets, firefighting foams, municipal waste, PFAS salts, and polymers ([Longendyke et al., 2022](#)). For PFAS waste, full mineralisation requires defluorination of the fluorocarbon chain and functional groups, and oxidation of the carbon skeleton. For halogenated waste, this is achieved through unimolecular and bimolecular reactions with flame radicals produced by combusting hydrocarbon fuels ([Hakeem et al., 2024](#)). These reactions aim to convert PFAS into carbon dioxide (CO₂), water (H₂O), hydrogen fluoride (HF) and or sulphur oxides (SO_x) ([Altarawneh et al., 2022](#); [Brunn et al., 2023](#); [Shields et al., 2023](#)). HF is a toxic and highly corrosive gaseous by-product and is neutralised in modern incinerators using pollution control systems such as wet or dry scrubbers ([Hagarty, 2023](#), [Vargette et al., 2023](#); [Wang et al. 2015](#)).

In addition to gaseous emissions, inorganic fluorinated residues and metal fluorides may remain in the bottom and fly ash or volatilise, as incineration does not destroy metals ([Strandberg et al. 2021](#)). Fluoro-dioxins, fluoro-benzofurans and fluorinated aromatic compounds may also be produced if PFAS are incinerated with other mixed wastes ([Davies et al., 2024](#); [McKay et al., 2022](#)). Additionally, perfluoroalkyl substances, along with standard combustion pollutants such as carbon monoxide, SO_x, nitrogen oxides (NO_x), hydrogen chloride, and trace metals may also be released, originating from other waste components that may also contain PFAS. The specific emissions depend on the combustion conditions and waste composition ([Winchell et al., 2021](#); [Meegoda et al., 2022](#)).

Thermal destruction of most organic compounds occurs between 590°C and 650°C ([US EPA, 2022](#)). However, certain PFAS require higher temperatures of >1000°C due to the

strength of the carbon–fluorine (C-F) bond, which has a high bond dissociation energy of 502 kJ mol⁻¹, making it extremely stable ([ECCC and Health Canada, 2024](#); [Longendyke et al., 2022](#)). This bond strength arises from fluorine’s high electronegativity, low polarizability, and small atomic radius ([Cousins et al., 2020](#)), making it up to 1.5 times stronger than carbon–chlorine (C–Cl) bonds ([US EPA, 2024](#); [INERIS, 2023](#); [Parsons et al., 2008](#)). As such, complete mineralisation of PFAS requires high temperatures, extended residence times, and precise operational controls. Determining these optimal conditions remains an active area of research ([Winchell et al., 2021](#)).

PFAS thermal treatment is a highly variable and complex process, involving thermodynamics, kinetics, and numerous physical and chemical reactions, all of which are strongly influenced by operational conditions. Different compounds break down by distinct thermal degradation pathways ([Krug et al. 2022](#); [Longendyke et al. 2022](#); [Takahashi et al., 2020](#); [Alinezhad et al., 2023](#)). Many PFAS contain C-C and, in some cases, C-H bonds, along with various functional groups. It’s unknown where these bonds will always break during incineration. The concern is that C–C bonds can break at lower temperatures, leaving behind C–F fragments. If the local energies and free radical concentrations are low this may result in the formation of volatile, ultra-short or short-chain PFAS and fluorinated greenhouse gases, collectively referred to as products of incomplete combustion (PICs) ([Paultre et al., 2022](#); [Van Caneghem et al., 2025](#)).

In sub-optimal conditions, these include persistent perfluorinated radicals and secondary fluorinated compounds that may remain in emissions or residues in low quantities. Instead of achieving full mineralisation, these intermediates may recombine into stable, persistent by-products, such as perfluoroalkyl carboxylic acids (PFCAs) in the atmosphere, thereby increasing the risk of environmental contamination by wet and dry deposition ([Altarawneh, 2021](#); [Altarawneh et al., 2022](#); [Goldenman et al., 2019](#); [Schroeder et al., 2021](#); [Watanabe et al., 2016](#); [Meegoda et al., 2022](#); [Roesch et al., 2020](#); [J. Zhang et al., 2023](#)). Many PICs are likely to be highly mobile due to their low molecular weight ([Brendel et al., 2018](#); [US EPA., 2025](#)) and are likely to partition into the atmosphere ([Bakker et al., 2021](#)). Others may be larger than the original compounds, formed through the recombination of two large radicals ([US EPA, 2024](#)).

The formation of PICs might primarily occur in post-combustion zones lacking sufficient temperature and poorly mixed oxygen deficient pockets ([Blotevogel et al., 2023](#)). In these conditions, fluorine’s high electronegativity and reactivity can disrupt flame chemistry by reacting with and neutralising key combustion radicals, terminating chain-branching reactions and inhibiting flame propagation, which may limit complete PFAS mineralisation ([National Research Council., 2000](#); [Maga et al., 2021](#); [Hakeem et al., 2024](#)). However, PIC formation during PFAS thermal degradation is highly complex and variable ([Burgess et al., 1995](#)), with many combustion by-products likely still unmeasured and unquantified. It is therefore key to distinguish between target destruction where PFAS concentrations are reduced, often with partial defluorination, and complete destruction, which confirms full mineralisation and defluorination.

Knowledge gaps also remain regarding PFAS atmospheric behaviour, including transport, transformation, and long-range impacts ([Lin et al., 2022](#); [Faust, 2022](#); [Environment Agency, 2025](#)). The formation of some PICs, such as CF_4 and C_2F_6 , is particularly undesirable due to their high global warming potentials ($\sim 5,700$ and $\sim 11,900$ CO_2 equivalents, respectively), long atmospheric lifetimes, and strong infrared adsorption ([Say et al., 2021](#); [Verma et al., 2023](#); [Sovacool et al., 2021](#); [Greenhouse Gas Protocol, 2016](#)). That said, perfluorocarbons such as, CF_4 and C_2F_6 are considered relatively non-toxic gas-phase PFAS ([Krug et al., 2022](#); [Winchell et al., 2021](#); [US EPA, 2019b](#)).

When PFAS containing-firefighting foams and fluoropolymer products like polytetrafluoroethylene (PTFE) undergo thermolysis, PFCAs including trifluoroacetic acid (TFA) and other fluorinated compounds may also persist, complicating the incineration process and increasing the risk of secondary pollution ([Ellis et al., 2001](#); [Mattila, 2024](#)). TFA is possibly the most abundant PFAS in the environment and is frequently detected in water, soil, and plant tissues, raising questions about its long-term environmental accumulation and potential ecological and human health impacts ([Arp et al., 2024](#); [Fidra, 2025](#); [Freeling et al., 2022](#), [Hartz et al., 2023](#); [Freeling et al., 2022b](#)).

The efficiency of PFAS incineration and the nature of resulting by-products depend on operational and waste specific factors. These conditions may lead to non-destruction, partial destruction, or complete destruction of the target compounds, as illustrated in **Figure 4** below:

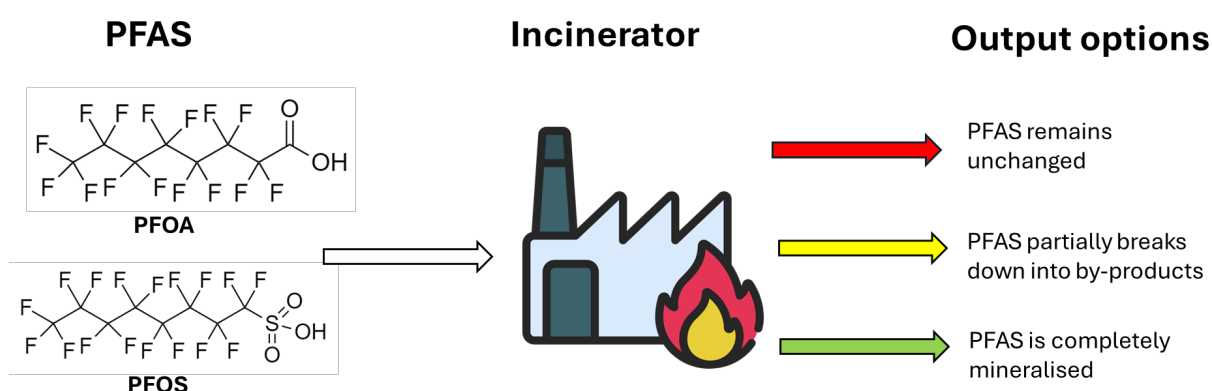


Figure 4. Pathways of PFAS destruction during incineration, modified and redrawn from [Meegoda et al., 2022](#)

Waste Matrix Composition: Destruction efficiency varies with molecular structure, concentration, and physical state of the PFAS, plus whether they are surface deposited or embedded within a polymeric structure. Low moisture and low non-combustible content improve calorific value and combustion efficiency. However, excessively high-calorific content is avoided, often requiring waste blending ([Coyle et al., \(2021\)](#)).

Operational and Reaction Conditions: Incineration efficiency is primarily determined by the "3T" principles, temperature, residence time and turbulence. High temperatures break C–F bonds; adequate residence time allows for complete combustion by influencing the extent of secondary decomposition reactions; and turbulence ensures that oxygen is

evenly distributed. These principles are crucial for achieving efficient and complete combustion of waste including PFAS in HTI, ensuring minimal environmental impact.

Chamber Environment: The combustion chamber environment including water vapour, reactive radicals, mixing, and the presence of catalytic surfaces such as trace metals or coexisting substances may influence thermal combustion pathways, potentially altering PFAS breakdown and PIC formation in the secondary combustion chamber ([Hakeem et al., 2024](#); [Wang et al. 2023](#); [Wang et al., 2022](#)). [Lott et al. 2022](#) provides a summary of catalytic approaches for gas-phase PFAS abatement.

To support research and improve understanding of PFAS destruction through incineration, the US EPA has compiled a PFAS Thermal Treatment Database ([ITRC,2023](#); [US EPA, 2022b](#)) to help synthesise the current body of research.

Despite growing research, knowledge gaps remain in understanding the thermal decomposition of PFAS and their emissions. HWIs and cement kilns ([section 5.1.4](#)) which run at higher temperatures and longer residence times than municipal waste incinerators (MWIs), are likely more effective for gas-phase PFAS mineralisation which is a critical step in any thermal process ([Hakeem et al., 2024](#)).

3.2 Hazardous Waste Incineration Process

Rotary kilns are mainly used for the incineration of hazardous waste, providing reliable and flexible processing for mixed waste streams. Pre-treatment steps can improve combustion efficiency by removing contaminants, increasing surface area (grinding or pelletising), homogenising waste for consistency, and dehydrating materials. The pre-treatment process for PFAS contaminated aqueous waste typically uses granular activated carbon (GAC) to adsorb PFAS followed by either HTI or thermal reactivation of the spent carbon.

Successful combustion of waste requires good waste homogenisation, a sufficient and well mixed air supply, adequate residence time, and low moisture and inert content to maintain high calorific value. HWI generally occurs in two stages (**Figure 5**) ([Cao et al., 2018](#); [National Research Council., 2000](#); [Tow et al.,2021](#); [Giraud et al.,2021](#)):

1. Primary combustion in the rotary kiln: This stage removes moisture and combusts volatile compounds. The slow rotation and inclined design of rotary kilns promote thorough mixing and waste air contact, ensuring efficient and consistent combustion.

2. Oxidation in the secondary combustion chamber/afterburner (900°C–1,200°C): Flue gases and particulates that were not destroyed in the rotary kiln are exposed to high temperatures with a residence time of two to three seconds, achieving over 99.9% destruction efficiency for PFAS ([Blotevogel et al., 2023](#); [US EPA, 2024](#)).

To reduce emissions, flue gases can undergo multi-stage treatment, including wet scrubbing, filters, carbon adsorption etc (which may generate separate waste streams), and high temperature oxidation to remove particulates, dioxins, furans, acidic gases, and

heavy metals. These processes can be supported by bag filters and activated carbon injection. Continuous emissions monitoring tracks pollutants such as carbon monoxide, CO₂, SO₂, nitrogen oxides, dioxins, furans, hydrogen fluoride (HF), and hydrogen chloride. HF requires careful containment, neutralisation, and monitoring to protect both incinerator infrastructure and worker safety. The remaining bottom ash, slag and effluent receive additional treatment or are sent to hazardous waste landfills ([Hagarty, 2023](#)). In the EU, ash from incineration of certain wastes may be reused in construction, such as road building, cement aggregate or sent to landfill ([Federal Environmental Agency, 2024](#)). However, it is the Environment Agency's understanding that ash from HWI is not reused in construction materials in England.

Fluctuations in temperature and oxygen levels in the post-combustion zone can also create cold spots (below 1000°C) where PFAS can undergo alternative reaction pathways ([Murakami et al., 2025](#)). Destruction efficiency also varies with waste composition and PFAS input method. PFAS introduced via the main burner with auxiliary fuel may experience different combustion conditions than when mixed in with solid waste, potentially leading to uneven breakdown ([US EPA, 2024](#)). Advanced gas treatment can capture some emissions, but volatile PFAS may escape during thermal treatment ([Li et al., 2019](#)). Detection remains a challenge, as current analytical methods often struggle to quantify low concentrations making precise quantification and destruction efficiency assessments challenging.

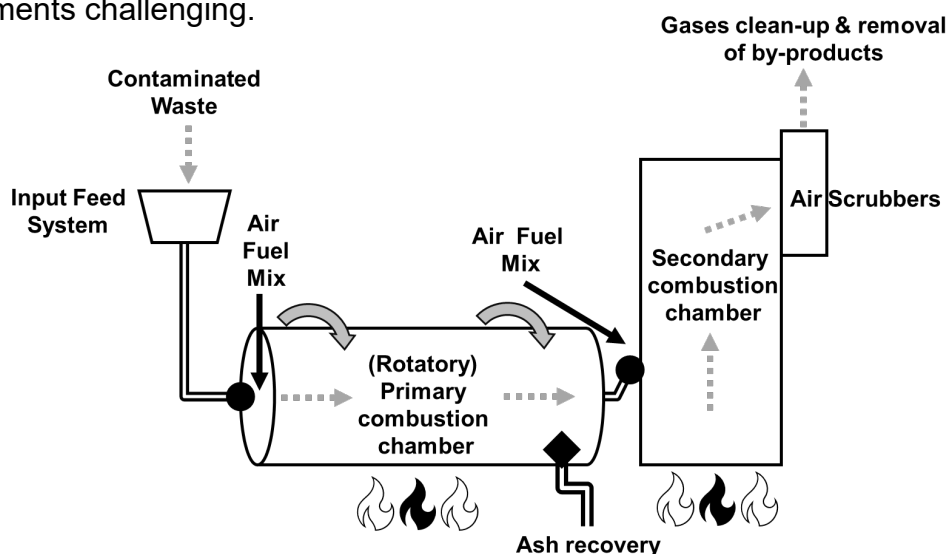


Figure 5. Simplified diagram of an incinerator for hazardous waste, converting waste into ash and gases ([Jiang et al., 2019](#)).

In Europe, the [Industrial Emissions Directive \(2010/75/EU\)](#) (IED) mandates a minimum incineration temperature of 850°C with a two second residence time to prevent environmental harm. For hazardous waste containing more than 1% halogenated organic substances (expressed as chlorine), this threshold increases to 1,100°C to ensure effective incineration ([Arkenbout, 2020](#)). The IED is implemented in the UK primarily through the [Environmental Permitting \(England and Wales\) Regulations 2016 \(EPR\)](#), which have been amended to reflect the UK's post-Brexit legal framework. However, these standards may not directly account for the higher temperature and stricter process controls required for PFAS.

Therefore, many incinerators may not consistently reach PFAS destroying conditions, raising uncertainties about PIC emissions ([Winchell et al., 2021](#); [Lohmann et al., 2020](#)). Capacity constraints further complicate management, especially as HWIs may not always be designed for bulk solids requiring pre-treatment before processing. In England, there is a lack of HWIs, with only two major HWI facilities accepting PFAS foam waste. In contrast, the UK has 57 municipal waste incinerators operating at 850–1,000 °C, which may be treating PFAS-containing waste unknowingly without guaranteeing complete mineralisation ([Section 4.6](#)) ([UK Parliament, 2025](#)). As a result, stockpiling waste pending destruction is a growing issue due to cost and capacity. There are options for regulatory actions that would allow for the export of these PFAS wastes for incineration or any new equivalent treatment techniques, pending increased UK capacity ([HSE, 2025](#)). However, a report for the Environment Agency ([WSP, 2023](#)) estimates that GB stocks of PFAS-containing foams, anticipated to range from 10,800 to 20,800 tonnes, would account for 5–20% of the UK's annual incineration capacity. Whilst other waste streams, including those regulated under the POPs framework will also compete for capacity, the report concluded that major shortfalls are unlikely given expected transition timelines.

Even when effective, PFAS incineration has environmental trade-offs: advanced exhaust treatment, transport and handling requirements. Limited HWI capacity often means long distance transport and increasing cost. Incomplete combustion of PFAS containing AFFF may release large amounts of PIC greenhouse gas emissions ([Kovacs et al., 2025](#)). While some facilities may recover heat for energy, PFAS destruction remains highly energy intensive making thermal treatment a resource demanding process ([Klein and Holmes, 2022](#)). This is especially true when incinerating AFFF-contaminated water, where most of the energy goes into evaporating water to treat a small, diluted amount of PFAS ([Maga et al., 2021](#)).

Between 2019–2021 HTI of PFAS contaminated soil in the UK and Europe cost ~£380–£1,700/m³ ([Concawe et al., 2024](#)) excluding transport. Disposal of PFOA containing firefighting foam or water is estimated at £350–£850 per tonne, with a best estimate of around £500, subject to inflation ([HSE, 2025](#); [WSP, 2023](#)). Further socioeconomic analysis of PFAS foam incineration is available at the European level through [Wood et al. \(2020\)](#) and ECHA Annex 15 restriction dossier ([ECHA, 2023b](#)), and for the UK, in the HSE's Annex 15 restriction dossier on PFAS in firefighting. An additional cost estimation model for PFAS remediation at high-risk sites is provided by [Jacobs, 2023](#).

Even with these challenges, HTI remains the most technically and economically feasible option for treating highly concentrated PFAS waste like firefighting foams. Its ability to reach the extreme temperatures required for PFAS breakdown makes it a critical part of the remediation toolbox ([Dirani et al., 2024](#); [Verma et al., 2023](#)). However, precise operational controls are important to guarantee mineralisation and prevent the release of PICs.

3.3 Challenges with Destruction Efficiency

The Basel Convention General Technical Guidelines for managing Persistent Organic Pollutants (POPs) define two key performance metrics for destruction: Destruction Efficiency (DE) and Destruction Removal Efficiency (DRE) ([UNEP](#)).

DE evaluates the overall effectiveness of a treatment process, such as incineration, by considering the PFAS content across all outputs, including gases, liquids, and solids. It is calculated as:

$$DE = \frac{M_{waste} - (M_{gas} + M_{liquid} + M_{solid})}{M_{waste}}$$

Where:

M_{waste} = mass of PFAS in waste

M_{gas} = mass of PFAS in output gas emissions

M_{liquid} = mass of PFAS in output liquid waste

M_{solid} = mass of PFAS in output solid waste

DRE, by comparison, measures only the efficiency of PFAS destruction in air emissions, excluding potential residues in liquid or solid waste. It is defined as:

$$DRE = \frac{M_{waste} - M_{gas}}{M_{waste}}$$

While DE and DRE are widely used to assess incineration performance, they do not account for PICs or other persistent degradation by-products that may form and remain undetected in emissions or residual waste. A high DE or DRE indicates a reduction in target PFAS compounds but may not guarantee complete mineralisation, as these metrics do not track the transformation of PFAS into other potential hazardous fluorinated derivatives ([US EPA, 2024](#); [Held and Reinhard, 2020](#); [Smith et al., 2024](#)).

Uncertainties remain regarding the effectiveness of current destruction processes as some PICs remain undetected by the analytical methods employed. For example, CF_4 a common PIC, is often undetected in studies. Achieving 99.99% DE of CF_4 requires temperatures of approximately 1,400°C with a one second residence time, though decomposition may begin at approximately 1,100 °C. Whereas C_2F_6 , another common PIC, decomposes at ~950°C and may achieve >99% DE at ~1050°C ([Krug et al. 2022](#)). Therefore, at temperatures of 850°C with high DRE, CF_4 and C_2F_6 may remain as the most prevalent gaseous by-products, raising questions about their persistence and complicating efforts to guarantee complete mineralisation ([Shields et al., 2023](#); [Watanabe et al. 2016](#)). At the same time, excessively high temperatures can also cause operational issues, including ash melting, clinker formation, reduced refractory lifespan, and increased maintenance costs.

CF₄ and C₂F₆ have been proposed as potential surrogates for monitoring fluorinated emissions and potentially evaluating destruction efficiency ([J. Zhang et al., 2023](#)). However, [Longendyke et al., 2022](#) indicates that using CF₄ alone may underestimate the extent of PFAS defluorination. Therefore, using multiple surrogates (HF, CF₄, and other compounds) with different properties may provide a broader measure of PFAS destruction along with targeted analysis. Further studies are needed to confirm whether their degradation reliably indicates complete mineralisation and the absence of harmful fluorinated by-products.

3.4 Regulatory Challenges in PFAS Emissions and Monitoring

Small amounts of PFAS that are not fully destroyed may remain in residual ash, be captured by flue gas treatment systems, or be released into the air. The effectiveness of these systems in capturing airborne PFAS is not well documented. Monitoring and analysis of emissions to confirm complete PFAS destruction is challenging. Inadequate analysis protocols risk failing to detect multiple PFAS compounds, leading to false negatives and overestimation of destruction efficiency.

PFAS can be transported through the atmosphere in both gas and particle phases, enabling long-range transportation ([D'Ambro et al., 2021](#); [Environment Agency, 2023](#)). However, the specific fate and transport mechanisms of PFAS in air are not fully understood. Partitioning from gas phase to particle phase is more favourable with increasing chain length and decreasing temperature ([Faust et al., 2022](#)). Particulate forms of PFAS are more likely to be captured by air filtration systems, whereas volatile, non-particulate PFAS are harder to trap and may pass through. At the same time, volatile and semi-volatile PFAS may then transform in the atmosphere into more persistent PFAAs. Although airborne PFAS emissions may be low in some waste streams due to their low concentrations, current techniques may lack the sensitivity needed for accurate detection ([Environment Agency, 2025](#)). Nevertheless, abatement is highly desirable as even trace level emissions are environmentally important due to their persistence and mobility.

Existing methods focus largely on water matrices, with limited applicability to soil, waste, or air. While accredited labs can detect PFOS and PFOA in water using liquid chromatography-tandem mass spectrometry (LC-MS/MS), accreditation for soil is limited, and no standardised method widely exists for monitoring and analysing air or waste ([Hofman et al., 2025](#)). Extraction and quantification of PFAS in these matrices can be further complicated by their presence at extremely low levels, often near or below detection limits, and by the complex nature of these sample types. Furthermore, LC-MS/MS currently targets only a limited subset of around 50 PFAS, with reference standards available for fewer than 120 PFAS compounds ([Sabba et al., 2025](#)). Additionally, while many studies have shown the presence of PFASs and PFCAs, less is known about the less stable precursors and intermediates.

Producing an accurate mass balance for PFAS in waste may also be challenging. Fluoride may interact with furnace materials (silica and alumina) during incineration ([Gehrmann et al., 2024](#)), causing possible inaccuracies in measurement. Output fluorine may be also distributed across undegraded PFAS, HF, PICs, and other fluorinated compounds, as well as in secondary streams like scrubber wastewater. Certain incinerator materials, especially metals, may possibly act as catalysts, potentially lowering destruction efficiency or creating unintended by-products. Alumina catalysts have demonstrated potential to reduce the energy demands associated with PFAS destruction ([Shields and Wallace, 2023](#); [Riedel et al., 2021](#)). However, further research is required to develop and understand the influence of catalysts on PFAS mineralisation ([Hakeem et al., 2024](#)).

Targeted analytical methods quantify specific PFAS compounds in water, soil, and sediments, however, they only cover a small subset of the broader chemical class. To better assess the total PFAS burden in a sample, it's crucial to use approaches that measure the bulk organofluorine content in complex matrices and broaden the scope beyond just the routinely targeted species. Advanced techniques such as Extractable and adsorbable Organic Fluorine (EOF and AOF), fluorine-19 nuclear magnetic resonance spectroscopy (^{19}F NMR), particle-induced gamma-ray emission (PIGE) spectroscopy and Total Oxidizable Precursor (TOP) Assay ([Houtz & Sedlak, 2012](#); [Ateia et al., 2023](#)), provide a more complete picture of the overall presence of PFAS in a sample. However, discrepancies exist between methods that measure sum parameters and those that detect individual substances, indicating that a portion of PFAS may still not be accounted for.

Given the diversity of PFAS structures, no single analytical technique can broadly quantify all PFAS present, necessitating a combination of targeted and non-targeted approaches. More detail on targeted and non-targeted approaches is provided elsewhere ([Smith et al., 2024](#); [De Silva et al., 2021](#); [Environment Agency, 2025](#); [Environment Agency, 2021](#), [RSC, 2023](#)). The US EPA notes that the current lack of standardised methods and limited data on method performance adds uncertainty to PFAS emission measurements. This results in inconsistent findings, making it harder for regulators, facilities, and technology developers to coordinate effectively. Reliable evaluation of PFAS destruction through incineration requires the ability to detect a broad mix of volatile, semi-volatile, polar, and non-polar compounds. That said, protocols for PFAS sampling and analysis for industrial emissions are becoming increasingly standardised.

To address these gaps, the US EPA is reviewing incineration practices and developing new analytical methods. OTM-45 is the most proven method and detects 50 semi-volatile polar PFAS but excludes ultra short chain compounds like CF_4 ([US EPA, 2021a](#)). OTM-50 complements this by targeting 30 non-polar volatile PFAS and PICs ([US EPA, 2024d](#); [Wallace and Smeltz, 2023](#); [INERIS, 2023](#)). OTM-55 is in development to detect non-polar semi-volatile and non-volatile PFAS, including fluorotelomer alcohols and fluorinated dioxins ([Envirotech, 2023](#); [Trozzolo and Howard, 2024](#)). Belgium has implemented a PFAS air monitoring method based on the OTM-45 sampling approach ([Hofman et al., 2025](#)). Researchers have also started to employ techniques such as Fourier transform infrared spectroscopy (FTIR) and chemical ionization mass spectrometry (CIMS) for analysis of fluorinated compounds in the gas phase ([Weitz, 2024](#)). Together, these

approaches aim to improve the accuracy and reliability of PFAS air monitoring during incineration. Monitoring these by-products, especially short chain fluorinated gases, is important for understanding the full environmental impact of PFAS incineration ([Vargette et al., 2023](#)). However, there's still a need for improved suspect lists and new identification tools to expand the scope of PFAS detection ([Megson et al., 2025](#)).

3.5 Regulatory Developments in Firefighting Foam Management

PFAS surfactants are key components in various firefighting foams (FFF) used to suppress Class B fires involving flammable liquids ([Barzen-Hanson et al., 2017](#)). These surfactants are typically produced via electrochemical fluorination or fluorotelomerisation. Foam types include Aqueous Film-Forming Foam (AFFF), Alcohol-Resistant AFFF, and fluoroprotein-based variants. AFFF, the most widely used, is often used interchangeably with the term "PFAS-containing foam". HTI remains one of the few proven methods for its destruction ([ITRC,2023](#)).

AFFF is a water-based formulation designed to suppress liquid fuel fires, particularly those involving petroleum hydrocarbons and chlorinated solvents. It is widely deployed in high-risk environments such as refineries, airports, military airfields, and offshore platforms ([Harding-Marjanovic et al.,2015](#)). Its effectiveness stems from fluorosurfactants that form stable, heat resistant films and foam blankets, rapidly isolating fuel from oxygen and reducing the risk of reignition ([ITRC,2023](#); [Dlugogorski & Schaefer, 2021](#); [Olsavsky et al., 2020](#)). Water evaporation further cools the fire, enhancing suppression ([Jahura et al., 2024](#)). Due to the persistence of PFAS, even a single use can result in long term environmental contamination, whether from training, incidents, storage, or disposal ([Reinikainen et al.,2022](#)).The Environment Agency estimates the annual emissions of PFAS associated with the use of FFF to be approximately 48 tonnes in Great Britain per year ([HSE,2025](#)). The disposal of PFAS contaminated materials, such as firewater runoff, training residues, and expired foam, presents environmental and economic challenges. Regulatory attention has grown, particularly around legacy AFFF contamination. AFFF formulations are typically grouped into two legacy types and one modern type based on PFAS content and environmental risk ([Horst et al.,2021](#); [Nathanail et al., 2024](#)).

Legacy PFOS Based AFFF: Manufactured mainly by 3M from the 1960s until 2002, these foams contained PFOS and PFHxS. Due to its persistence and toxicity, PFOS was restricted in firefighting foams in the EU. However, foams placed on the market before 27th December 2006 were permitted for use until 27th June 2011 in England ([Environment Agency, 2019](#)). Some countries may continue limited PFOS and PFHxS production for firefighting, contributing to global contamination ([Klein and Holmes, 2022b](#); [Brusseau et al., 2020](#); [Environment Agency, 2019](#); [ITRC, 2023](#); [Pancras et al., 2016](#)). In the USA, voluntary phase outs have already led to reduced public exposure ([New York Department of Environmental Conservation, 2020](#)). In England, monitoring programmes conducted by the Environment Agency, supported by certain academic studies, indicates a general

national downward trend in PFOS concentrations, reflecting the impact of regulatory restrictions and interventions since the early 2000s ([Environment Agency, 2025](#)).

Legacy Fluorotelomer Based AFFF: Produced from the 1970s to 2016 by manufacturers other than 3M, these foams contain polyfluorinated precursors that can degrade into perfluoroalkyl carboxylates (PFCAs), including PFOA ([Harding-Marjanovic et al., 2015](#)). In some formulations, these precursors may make up a large portion of the total PFAS content, making legacy fluorotelomer AFFF a source of potential PFAS pollution ([Houtz et al., 2013](#)). Under moderate pyrolytic conditions, some precursors may also transform into perfluoroalkyl substances ([Grenier et al., 2023](#)). However, the composition and behaviour of these precursors remain poorly understood, creating ongoing challenges for remediation and disposal. Careful management is essential to prevent further environmental contamination.

Modern C6 Fluorotelomer Based AFFF: More recent formulations use short chain C6 fluorotelomer surfactants, viewed as safer due to lower bioaccumulation and less toxic compared to C8 fluoro surfactants. However, they may remain highly persistent and mobile, increasing the risk of groundwater contamination ([ITRC, 2023](#)). These foams may degrade into compounds such as PFHxA, PFPeA, and 5:3 FTCA, which resist natural breakdown and accumulate in the environment ([Jahura et al., 2024](#); [Harding-Marjanovic et al., 2015](#); [Xiao et al., 2021b](#)). Some may also contain trace PFOA impurities or ultra short chain PFAS (e.g. C2 and C3 carboxylates) ([Barzen-Hanson et al., 2017](#)), raising additional considerations, particularly as occupations such as firefighting have been linked to PFAS exposure ([Lucas et al., 2023](#)). Limited data on long term effects has raised concerns over "regrettable substitution", where newer compounds may present similar risks to those they replaced.

In response, regulatory pressure has accelerated the shift toward fluorine free firefighting foams (F3), designed to offer similar performance to AFFF with reduced environmental impact. F3 foams are typically more biodegradable and less persistent. While not direct replacements, due to the absence of film forming properties, they have been successfully adopted across multiple sectors and have proven effective in certain scenarios. As well, F3 disposal is usually more straightforward and cost effective ([IPEN, 2018](#)). While some F3 meet established performance standards in controlled firefighting tests, broader adoption depends on sector specific validation, real world performance trials, and environmental management to confirm they are both effective and safe. The precise chemical composition of both AFFF and F3 remains unclear due to proprietary formulations. Although marketed as "fluorine free," some F3 products may still contain fluorinated compounds outside the OECD's PFAS definition. F3 foams may also require higher application volumes and may be less effective under extreme conditions ([Jahura et al., 2024](#); [HSE, 2025](#)). Transitioning to F3 also involves cost and operational challenges, particularly for infrastructure decontamination. PFAS residues persist in storage tanks, pipes, and equipment, requiring thorough cleaning to prevent cross contamination ([Lang et al., 2022](#)). As PFAS based FFF are phased out, accessible disposal options, safer alternatives, and effective remediation strategies will be key to managing ongoing contamination.

4. Optimising Operational Conditions for PFAS Incineration

4.1 Thermal treatment of Non-Polymer PFAS

As the temperature increases, some PFAS compounds may gradually volatilise and undergo gas phase reactions, with the byproducts formed largely depending on their volatility and the composition of the waste material. The effectiveness of PFAS destruction during HTI is influenced by a range of chemical and structural factors, such as the amount of fluorine, the length of the carbon chain, the degree of backbone saturation, the presence of functional groups, and the type of PFAS salt involved. **Figure 6** below illustrates a simplified chemical taxonomy of polymer and non-polymer PFAS.

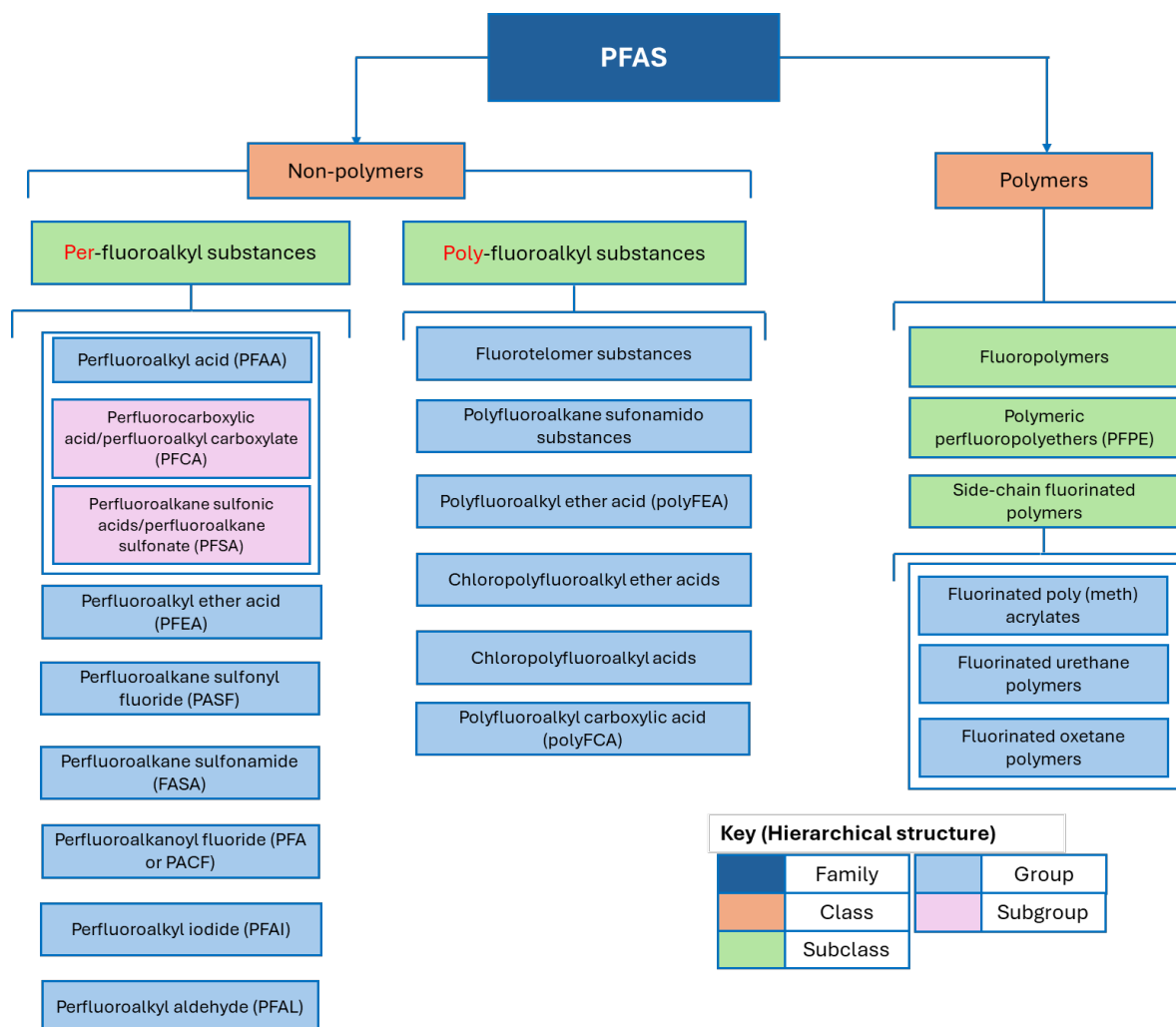


Figure 6. Simplified chemical taxonomy of PFAS, ranging from the family level to the subgroup level, modified and redrawn from (ITRC,2023).

Perfluoroalkyl sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs), both perfluoroalkyl acids (PFAAs), are among the most thermally stable fluorinated surfactants.

In contrast, polyfluorinated compounds tend to be less thermally stable than their perfluoroalkyl counterparts ([Grenier et al., 2023](#)).

Higher fluorine content and fully saturated carbon chains increase thermal stability, making PFAS more resistant to thermal decomposition ([Longendyke et al., 2022](#)). However, the effect of chain length on incineration efficiency remains unclear and is influenced by functional groups and other structural features. For instance, the decomposition of perfluorocarbons (PFCs) is chain-length dependent, with shorter-chain compounds like CF_4 being the most thermally stable ([Tsang et al., 1998](#)). In contrast, chain length may have little or no impact on PFCA decomposition rates ([Blotevogel et al., 2023](#)).

Thermal decomposition typically begins with the breakdown of non-fluorinated functional groups at relatively low temperatures ([Dixon, 2001](#)). However, the remaining fluoroalkyl group is highly stable, and complete destruction of its C–F bonds require significantly higher temperatures. This group may also react with other species which can promote the formation of a wide range of PICs ([INERIS, 2023](#)). The presence and nature of functional groups (e.g. COOH , OH , SO_3H) also influences thermal stability, with sulfonic acid groups being the most stable.

The thermal stability of PFAA salts also varies depending on the counterion ([ITRC, 2023](#)). For example, the 20% decomposition temperature of sodium perfluorooctanoate is 298°C , whereas for lithium perfluorooctanoate it is 341°C ([Kissa, 2001](#)). Perfluorosulfonate (PFSA) salts are typically more thermally stable than perfluorocarboxylate (PFCA) salts ([Vecitis et al., 2009](#)). Stability increases in the following order: ammonium < caesium < potassium < silver < lead < sodium < calcium = barium < lithium ([Wang et al., 2022](#); [Horst et al., 2020](#); [INERIS, 2023](#)).

The thermal stability of different non polymer PFAS groups follows a **general** hierarchy (most to least) ([Wang et al., 2022](#)):

- Perfluorocarbons (PFCs)
- Perfluoroacyl fluorides
- Perfluorosulfonic acids (PFSAs)
- Perfluorocarboxylic acids (PFCAs)
- Perfluoroether carboxylic acids (PFECA)
- Fluorotelomer alcohols (FTOHs)
- Perfluoroalkyl sulfonamides (FASAs).

Specific compounds follow a similar degradation trend, with $\text{CF}_4 > \text{C}_2\text{F}_6 > \text{cyclo-C}_5\text{F}_{10} > \text{C}_3\text{F}_8 > \text{PFOS} > \text{PFOA} > \text{HFPO-DA} > 6:2 \text{ FTOH} > \text{PFOSA}$ ([Bakker et al., 2021](#), [Blotevogel et al., 2023](#); [Xiao et al., 2021](#); [Adi and Altarawneh, 2022](#)).

Reactor materials ([Weber et al., 2024](#)) and conditions, such as oxygen and water presence, can affect PFAS thermal decomposition. For instance, heptafluorobutyric anhydride ($\text{C}_8\text{F}_{14}\text{O}_3$) decomposed at 150°C in a reactor containing alumina but remained stable up to 850°C in a tantalum or silver reactor ([Wang et al., 2022](#)).

Hydroxyl groups present on refractory materials such as silica (SiO_2) and alumina (Al_2O_3), commonly used to line combustion chambers in waste incineration systems, may play a catalytic role in the oxidation of PFAS under inert atmospheric conditions. In the case of SiO_2 , it is hypothesised that PFAS degradation may involve the formation of silicon tetrafluoride (SiF_4), with concurrent oxidation of the fluorinated carbon backbone to CO ([Van Caneghem et al., 2025](#); [Yamada et al., 2005](#); [Taylor et al. 2014](#); [Wang et al., 2023](#)).

Volatility also plays a key role in degradation promoting their oxidation, with PFCs being the most volatile, whereas fluorotelomer sulfonates (FTSAs) exhibit the lowest volatility ([Sasi et al., 2021](#)). Increased vapour pressure (measure of volatility) improves oxidation, but decomposition temperatures vary between PFAS types. Volatile PFAS typically desorb into the gas phase and decompose during combustion, while less volatile species may persist longer or degrade in solid waste. Volatilisation is therefore influenced not only by a compound's inherent volatility but also by its interaction with the solid surface ([Van Caneghem et al., 2025](#)). This can be important for incineration where PFAS bound within complex matrices such as soils or biosolids may exhibit altered volatilisation and decomposition pathways ([Hakeem et al., 2024](#)). PFAS may also form salts through interactions with organic and inorganic matter, altering their thermal behaviour. Therefore, predicting PFAS stability during thermal treatment based solely on their volatility may be overly simplistic.

Isomer structure also affects thermal degradation pathways and behaviour in water systems, with linear isomers typically being more resistant to breakdown than branched and ether isomers. These differences could be considered when developing PFAS remediation strategies to guarantee effective treatment ([Londhe et al., 2022](#); [Rayne and Forest 2009](#)).

A general comparative ranking of PFAS volatility (most to least) is shown below ([Wang et al. \(2022\)](#)). Across these same functional groups, vapor pressure generally increases with decreasing chain length.

- Perfluorocarbons (PFCs)
- Fluorotelomer carboxylic acids (FTCAs)
- Fluorotelomer alcohols (FTOHs)
- Perfluorinated carboxylic acids (PFCAs)
- Perfluorosulfonic acids (PFSAs)
- Fluorotelomer sulfonates (FTSAs)

Most PFAS compounds either decompose or enter the gas phase by temperatures ~ 400 - 700 °C, where they decompose into gaseous by-products or intermediates. Therefore, at lower temperatures or under inert atmospheric conditions, volatile organic fluorides (VOFs) may be formed instead ([Wang et al., 2022](#); [J. Zhang et al., 2023](#); [Zhao et al., 2024](#); [Chalivendra 2023](#)). Consequently, a loss of long-chain PFAS at a given temperature does not necessarily mean mineralisation. [Wang et al., 2022](#) concluded under oxygen rich conditions decomposition and defluorination of PFCAs, PFSAs and fluoropolymers starts at 120°C , 320°C and 200°C respectively. However, to reach 80% defluorination

temperatures of >700°C are needed. Therefore, to achieve near mineralisation, incineration of non-polymer PFAS should likely be conducted at temperatures of at least 1000 °C in the secondary combustion chamber, regardless of residence time ([Blotevogel et al., 2025](#); [Weitz, 2024](#)).

4.2 Thermal treatment of Polymer PFAS

Polymeric PFAS are large, complex molecules composed of repeating monomer units and are classified into three main subclasses: fluoropolymers, polymeric perfluoropolyethers (PFPEs), and side chain fluorinated polymers ([Buck et al., 2011](#); [Environment Agency, 2021](#)). Compared to side chain fluorinated polymers, PFPEs have C–F bonds on a carbon only backbone and are largely considered highly stable and persistent ([Henry et al., 2018](#)). Among fluoropolymers, polytetrafluoroethylene (PTFE), commonly known as Teflon®, is the most widely produced and studied. PTFE consists of repeating tetrafluoroethylene units $[CF_2-CF_2]_n$ and begins thermal degradation at approximately 250°C by random chain cleavage and depolymerisation ([INERIS, 2023](#); [Huber et al., 2009](#); [Améduri and Hori., 2023](#)).

Limited data is available on the identities and volumes of PFAS polymer types used in Europe, as polymers are generally exempt from EU and UK REACH registration obligations and are not regulated for most uses and products. However, globally fluoropolymers are the second-largest subgroup of PFAS, with annual production reaching several hundred thousand tonnes, second only to fluorinated gases ([Evich et al., 2022](#); [Dalmijn et al., 2025](#)). Although their larger size reduces bioavailability compared to monomers, PFAS polymers may still present environmental and health risks across their life cycle and warrants further research ([European Environment Agency, 2025](#)).

Fluoropolymers, including PTFE, are typically incinerated in Municipal Waste Incinerators (MWI) or landfilled. However, studies on PTFE pyrolysis ([section 5.3.17](#)) and incineration have produced mixed results regarding PFAS emissions. Most research on fluoropolymer thermal degradation focuses on temperatures ranging from 400°C to 1,050°C, with some studies indicating that heating PTFE between 250°C and 600°C, particularly under uncontrolled conditions, can generate PFCAs and other short chain fluorinated compounds such as TFA ([Cui et al; 2019](#); [Lohmann et al, 2020](#); [ECHA, 2023b](#); [Ellis et al., 2001](#); [Vecitis et al., 2009](#); [Giannetti, 2005](#); [Garcia et al., 2007](#); [Danz et al., 2019](#); [Schlummer et al., 2015](#); [Garavango et al., 2024](#); [Puts et al., 2014](#); [Conesa and Font, 2004](#); [Bhadury et al., 2007](#); [Simon and Kaminsky, 1998](#)).

While targeted analysis of fluoropolymer incineration has proven useful in detecting specific compounds, its limitations are evident, with total fluoride recovery below 50% in some controlled laboratory settings. Therefore, current understanding of the processes driving thermal byproduct release from fluoropolymers remains limited and requires further research ([Ellis et al., 2001](#); [Duchesne et al. 2020](#); [Ajeti et al., 2024](#)).

[Myers et al. 2014](#) identified numerous thermal decomposition products of polychlorotrifluoroethylene (PCTFE), a widely used commercial fluoropolymer. These included 29 perhalogenated carboxylic acids and 21 chlorine and fluorine substituted polycyclic aromatic hydrocarbons, such as halogenated benzenes and naphthalenes. These findings highlight the complexity of fluoropolymer thermal decomposition. Recycling is also likely not a viable option ([ECHA, 2023b](#)).

Side-chain fluorinated polymers have significant decomposition by 600 °C. Under incineration like lab conditions (1000 °C, 2 s residence, 85% excess air), over 99.9% destruction efficiency was achieved, with minimal residual fluorinated radicals ([Yamada et al., 2005](#)). A bench-scale study by [Taylor et al. 2014](#) investigated the combustion of fluorotelomer-based polymers under typical municipal waste incineration conditions (1000 °C, 2 s residence time, with methanol fuel). No PFOA emissions were detected.

Other studies suggest that municipal incineration of fluoropolymers at temperatures (800°C) does not substantially contribute to PFAS emissions, with PTFE decomposing nearly completely at 800°C ([Ajeti et al., 2024](#); [Gehrmann et al 2024](#); [Aleksandrov et al., 2019](#); [Bakker et al., 2021](#); [Améduri and Hori., 2023](#)). [Arhami Dolatabad et al., 2025](#) examined the thermal breakdown of PTFE, PCTFE, and PVDF between 200–890°C and found no PFAS formation under any conditions. In any case, MWI may be only able to handle limited amounts of fluoropolymers because their thermal decomposition releases hydrogen fluoride, which is highly corrosive ([Dams and Hintzer, 2016](#); [Lohmann et al., 2020](#)).

Discrepancies in studies likely result from differences in the by-products analysed, variations in experimental conditions, and whether the research was conducted at laboratory or full scale. By-product formation depends on multiple factors, including temperature, oxygen availability, humidity, waste composition, residence time, and the presence of catalysts.

To date, no direct studies have identified polymeric PFAS residues in incinerator ash. However, [Yang et al. 2021](#) demonstrated that small quantities of microplastics persist in bottom ash after incineration. While their study did not detect PTFE or other fluoropolymers among the ash residues, the presence of polymeric PFAS cannot be entirely ruled out. The assumption is that polymeric PFAS degrade effectively at incineration temperatures (~800°C) and is assumed an insignificant source of PFAS in flue gases for municipal waste incinerators. However, further research is needed to clarify the fate of fluoropolymers during incineration and PICs, as approximately 80% of fluoropolymer waste in the European Economic Area is processed through municipal waste incinerators with energy recovery ([ECHA, 2023](#)).

Among fluoropolymers, perfluoroethylene based polymers exhibit greater thermal stability than perfluorophenylene based polymers. Fully fluorinated materials, such as C₂F₄ and C₃F₆ based polymers, are the most resistant to degradation. The presence of monomers and processing additives in fluoropolymer resins may influence the composition and toxicity of degradation by products ([Wang et al., 2022](#); [INERIS, 2023](#)). **Figure 7** below

summarises their thermal decomposition initiation temperatures under oxidising conditions.

Common fluorinated by-products generated during PFAS thermal degradation include **Fluoropolymers**: CF_4 , C_2F_6 , CHF_3 , C_3F_6 , CClF_3 , C_4F_8 , $\text{C}_2\text{Cl}_3\text{F}_3$, HF, TFA, and other perfluorinated gases. **PTFE**: CF_4 , C_2F_6 , C_3F_6 , C_2F_4 , and other fluorinated compounds **PFOS**: CF_4 , C_2F_6 , CHF_3 , $\text{C}_2\text{H}_2\text{F}_2$, HF, COF_2 ([Garcia et al., 2007](#); [Kitahara et al., 2009](#); [Aleksandrov et al., 2019](#); [Ajeti et al., 2024](#); [Hughey et al., 2024](#)).

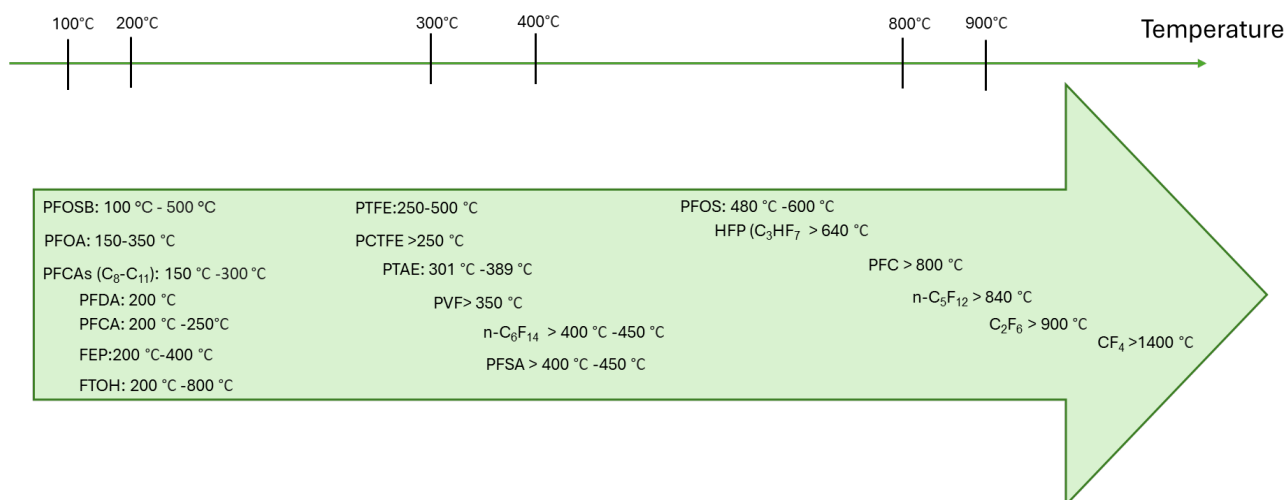


Figure 7. Summary of PFAS thermal decomposition initiation temperatures under oxidising conditions, derived from theoretical and experimental data in the literature. This diagram highlights the most studied PFAS, with reference temperatures that may vary based on operating conditions and waste matrix composition. Modified and redrawn from ([INERIS, 2023](#)).

4.3 Laboratory Studies of PFOS and PFOA

PFOS and PFOA are among the most extensively studied and frequently found non-polymer PFAS in waste. While various studies suggest different breakdown temperatures, actual conditions required for complete mineralisation may be underestimated ([Horst et al., 2020](#); [Feng et al., 2015b](#)). Research indicates that PFOA begins to degrade between 300°C and 350°C ([Krusic and Roe., 2004](#); [Krusic et al., 2005](#)), while PFOS degradation starts at approximately 400-600°C. [Taylor and Yamada 2003](#) investigated PFOS incineration using a bench-scale quartz reactor at 600 °C and 900 °C. At 900 °C, with a two-second residence time, less than 0.05% of PFOS remained detectable. PFOS by-product levels were lower at 900 °C compared to 600 °C.

While decomposition starts above ~300°C for PFOA ([Stockenhuber et al., 2019](#)), for complete PFAS mineralisation, incineration temperatures appear to need to reach or exceed 1,000°C, with excess air and a minimum residence time of two seconds. [Rocchio et al. \(2025\)](#) demonstrated that incineration of PFOA in a pilot-scale furnace results in the

formation of smaller PFCAs. Theoretical modelling at peak temperatures between 750–850 °C predicted the generation of TFA and other short-chain PFAS by-products.

Interestingly, [Trang et al. \(2022\)](#) demonstrated that PFCAs can be effectively degraded at low temperatures via a sodium hydroxide-mediated defluorination process in polar aprotic solvents, achieving 78–100% mineralisation to fluoride within 24 hours.

The use of additives presents a promising approach to enhancing defluorination within incinerator furnaces. Mineralisation rates can be improved using calcium-based additives such as calcium hydroxide $\text{Ca}(\text{OH})_2$, which stabilises fluorine as CaF_2 reducing the required temperature for complete breakdown. Additionally, additive injections can be implemented at various stages of the incineration process ([Abou-Khalil et al., 2024](#); [Wang et al., 2013, 2011](#); [Riedel et al., 2021](#)).

[Murakami et al., 2025](#) reported that incineration >850 °C achieved a destruction efficiency of 99.999% for both PFOA and PFOcDA. However, destruction efficiency dropped significantly at temperatures below 700 °C.

[Shields et al. \(2023\)](#) demonstrated that temperatures above 1,090°C achieved efficient PFAS destruction (>99.99%) with minimal by-products. However, at temperatures below 1,000°C, while PFAS destruction remained high, there was an increase in emissions of volatile PFAS. [Mattila, \(2024\)](#) investigated AFFF incineration, confirming effective degradation of PFCAs and PFSAAs above 1,100°C with minimal PIC formation. However, lower temperatures (~800°C) resulted in emissions of short-chain PFAS, including TFA, and novel volatile compounds despite generally acceptable destruction efficiencies for PFSAAs. The study also identified novel PFAS emissions, including volatile compounds that could pose exposure risks to workers handling AFFFs, and found that certain PFAS compounds could persist in furnace systems, especially during temperature fluctuations.

Studies by [Altarawneh et al., \(2022\)](#) incorporated 56 reaction pathways for PFAS vapour destruction in a plug flow reactor. Their model predicted that PFAS decomposition begins at 747°C, with complete mineralisation at 1,227°C after a two second residence time. However, further field validation is required to confirm whether these conditions are consistently achievable in full scale incineration facilities ([J. Zhang et al., 2023](#); [Khan et al., 2020](#)).

[Cornell and Burke \(2024\)](#) highlighted previously unexamined fluorocarbon oxidation pathways that may improve PFAS destruction efficiency in incinerators. They identified nitric oxide (NO) as a potential additive that could lower temperature requirements for PFAS destruction, suggesting further research is needed on CF_3O_2 and other fluorocarbon derived radicals to optimise incinerator performance.

[Wang et al. \(2023\)](#) studied the gas phase breakdown products of PFCAs using a furnace combined with FTIR spectroscopy. Their findings suggested that fluorocarbon radicals act as key intermediates in the decomposition process, driven by oxidation from hydroxyl radicals ($\text{OH}\cdot$).

Modelling studies offer further insight into PFAS decomposition pathways. [Weber et al. \(2023\)](#) estimated that PFOA starts degrading at around 400°C. Their findings suggest that destruction removal efficiency above 99.99% are achievable at temperatures exceeding 700°C, though experimental validation remains limited. [Weber et al. \(2022a, 2022b\)](#) investigated PFOS decomposition in a lab scale incinerator and identified difluorocarbene (CF_2) as a key product from the high temperature breakdown of the perfluorocarbon backbone. They proposed that CF_2 can react with oxygen or hydroxyl radicals to produce $\text{FCO}\cdot$ and COF_2 , which help drive the complete mineralisation of PFOS into CO_2 and HF. Additionally, temperatures above 850 °C and with 10,000 ppm water vapour, PFOS thermal decomposition under a helium atmosphere showed a significant reduction in fluorocarbon concentrations.

[Xu et al. \(2025\)](#) confirmed that PFHxA (substitute to PFOA) decompose into fluorocarbon radicals (CF_2 and CF_3) and intermediates like acyl fluorides, which play a key role in forming secondary by-products. A key pathway identified involved the breakdown of PFAS into ketenes via acyl fluoride formation.

[Narimani et al. \(2022\)](#) demonstrated that adding water vapour to oxidising conditions alters the thermal decomposition by providing additional hydrogen atoms, which facilitate HF formation. Their study found that excess water vapour promotes COF_2 generation, which afterwards decomposes into HF rather than forming CF_4 and C_2F_6 .

Hence, a reliable source of hydrogen (H atoms, H bonds, CH_4 , H_2O) and maintaining an adequate hydrogen to fluorine (H/F) ratio may be important for the effective incineration of PFAS-containing wastes. In the absence of hydrogen, reactive intermediates such as CF_2 carbenes and CF_3 radicals can recombine or react with fluorine atoms to form CF_4 and C_2F_6 . To achieve full mineralisation and reduce the formation of PICs, sufficient hydrogen must be available in the combustion environment ([Weitz, 2024](#)).

For the thermal decomposition of PFCAs, computational studies show that the lowest-barrier pathway proceeds via α -lactone formation and HF elimination, followed by rapid breakdown into a perfluoroaldehyde and CO. In contrast, PFSA decompose via an α -sultone intermediate, also eliminating HF, and yielding perfluoroaldehydes and SO_2 ([Weitz, 2024](#); [Khan et al. 2022](#); [Khan et al. 2020](#)). Similar mechanisms have been proposed for HFPO-DA/GenX ([Adi and Altarawneh, 2022](#)).

Computational-scale studies report 99–99.99% destruction of PFOA and PFOS at 650–800 °C but PICs are often excluded. Computational studies also face several limitations: they are often restricted to the gas phase and therefore exclude surface interactions, are limited by the chosen level of theory, and tend to focus on short-chain PFAS that may not adequately represent the behaviour of longer-chain, more environmentally relevant compounds ([Weitz, 2024](#)). Additionally, current models may overlook low-temperature reaction pathways, limiting their ability to accurately assess PFAS destruction under suboptimal combustion conditions. Therefore, while certain PFAS are thermally unstable, breaking the resilient C–F backbone of PFOS/PFOA requires higher temperatures and combustion-driven free radical chemistry. Complete mineralisation is achievable but

depends on excess hydrogen, moisture, and flame radicals to promote C–F bond cleavage and minimise stable PIC formation.

Overall, while progress has been made, knowledge gaps seem to remain in the thermal decomposition of PFAS. These include the impact of directly controlled parameters such as fuel, oxygen levels, PFAS ratio, and water content. The effects of indirectly controlled factors like waste composition, soil, and AFFF components. Other gaps include the influence of PFAS headgroup and chain length, the role of radical intermediates in destruction and recombination, and the underlying processes and kinetic bottlenecks in complex wastes such as soil and AFFF.

4.4 Thermal treatment of GAC

Granular activated carbon (GAC) ([Section 5.2.1](#)) is a widely used technology for removing PFOS and PFOA from contaminated water. Once saturated, GAC can undergo low temperature vaporisation/regeneration and high-temperature reactivation to restore some of its adsorption capacity and remove adsorbed substances. This process can be carried out at commercial offsite thermal GAC reactivation facilities and involves drying (100°C), desorption (100°C–250°C), pyrolysis (200°C–750°C), and oxidation (800°C–1000°C) ([Ling et al., 2025](#)). Experimental evidence suggests that PFAS thermal destruction occurs in two stages: first during reactivation of GAC, and second when the off gas is treated at 1,000°C.

Most PFAS destruction occurs in afterburners at temperatures above 885°C. Offsite thermal GAC reactivation offers several advantages, such as reducing media disposal and replacement costs, lowering greenhouse gas emissions, and providing a sustainable supply by reusing reactivated GAC ([Ling et al., 2025](#)).

However, uncertainties remain regarding the potential for incomplete destruction ([Wang et al., 2024](#)), suggesting that for complete mineralisation, reactivating spent GAC may require temperatures of 1000°C or higher ([Siriwardena et al., 2021](#)). Although the temperatures required for effective PFAS mineralisation will vary depending on the compound's structure and the specific operational parameters of the incinerator. The US EPA highlight the temperatures required to achieve 99.99% DRE of GAC depend on contaminant concentrations and residence time, but generally range from a minimum of ~885 °C to a maximum of ~1,316 °C ([US EPA, 2024](#)).

GAC may alter the thermal decomposition pathways of PFAS and accelerate thermal PFAS decomposition, allowing for potentially lower temperatures for regeneration, as some PFCA decomposition has been observed at temperatures as low as 200-700°C in bench scale studies ([Xiao et al., 2021](#); [Sasi et al., 2021](#); [Sun et al., 2024](#); [Watanabe et al., 2018](#)).

While regeneration can include lower-temperature methods such as treatment with brines, solvents, oxidants, or biological processes, these approaches are generally less effective for GAC than thermal reactivation ([US EPA, 2024](#)). Experiments examining the thermal

stability of adsorbed PFOS/PFOA on GAC at temperatures between 700 and 1000°C revealed an imbalance in mass, indicating the loss of some volatile organofluoride compounds ([Watanabe et al., 2018](#); [2016](#)). [Xiao et al., 2021](#) noted high mineralisation of PFOA and PFOS (>80%) occurred at temperatures above 700–800 °C. Accompanied by near complete PFOA and PFOS decomposition (>99.9%). [DiStefano et al., 2022](#), tested PFAS destruction at a full-scale carbon reactivation facility using PFAS-laden GAC. Spent carbon moved through temperature zones from ~398–454°C to ~954°C and results showed >99.99% PFAS destruction. However, the fluoride mass balance was only 61.4%, which may reflect the formation of PICs that were not captured by the analytical method.

Although carbon reactivation systems, when combined with off-gas incineration and gas scrubbing units, show potential to remove PFAS from activated carbon and achieve destruction, the available data on PFAS-laden GAC reactivation remain limited. Further research and development are needed to optimise operating conditions and ensure safe, effective treatment, particularly under full-scale operating conditions, across different types of carbon, and with comprehensive measurement of PICs ([Gagliano et al., 2023](#); [Sonmez Baghirzade et al. 2021](#)).

4.5 Hazardous Waste Incinerator Studies

Although extensive research exists on PFAS thermal degradation ([Stockenhuber et al., 2019](#); [Altarawneh et al., 2022](#); [Sasi et al., 2021](#); [Xiao et al., 2021](#); [Crownover et al., 2019](#)), global field scale data remain scarce, particularly for less studied PFAS. Research on PFAS destruction in HWIs, including rotary kilns used in industrial applications, remains limited globally, as summarised in Table 1.

Most studies focus on specific waste streams, such as PFAS containing FFF and contaminated soils, but thorough characterisation of air emissions and potential by-products during incineration is lacking. This knowledge gap is largely due to the absence of reliable methodologies for assessing destruction efficiency and tracking the formation of PICs. Existing studies primarily examine targeted PFAS compounds rather than the full range of degradation by-products, making it difficult to determine the overall effectiveness of incineration in real world conditions. Further research would improve understanding of PFAS fate during incineration, validate destruction efficiencies under operational conditions, and more fully characterise the formation of fluorinated by-products in HWIs treating PFAS containing waste ([Weitz, 2024](#)). Although laboratory studies suggest that PFOS and PFOA mineralisation can be achieved at lower temperatures, real world incineration conditions introduce additional variables.

Table 1. Examples of real world HWI studies

Source and Country	Temperature range noted	Description
Japanese Ministry of the Environment (2013) , Japan	1,100°C in the rotary kiln and 900°C in the secondary furnace with an 8 second residence time	Investigated PFOS containing FFF incineration in a commercial scale HWI. Achieved >99.99% destruction efficiency through pre and post combustion analyses across various waste streams. Batch feeding of PFAS containing FFF caused combustion temperature fluctuations, potentially reducing destruction efficiency and increasing harmful by product formation.
Alaska LLC (2019) , USA	Up to 815°C for kiln and secondary combustion temperature of 980-1200°C, residence times not specified.	Pretreatment soil contained 21 of 24 tested PFAS, including PFOS (up to 7.24 mg/kg) and PFOA (up to 0.0765 mg/kg). Post-treatment soils and baghouse particulates largely showed PFAS below detection limits, except for low levels of PFOS (0.0003–0.0022 mg/kg) and PFHxS in some baghouse samples. Air emissions included 10 PFAS compounds with a total average release of 0.0791 mg/h, including PFOA at 0.0185 mg/h. Potential contamination in flue gas sampling indicated further investigation is needed to fully quantify emissions. A wet scrubber was subsequently installed to control HF before commercial operation. Destruction efficiency not stated.
Clean Harbors EA Engineering (2021) , USA	1034°-1098 °C (kiln), 1122°-1154 °C (afterburner); 2–3 second gas residence time	Two testing campaigns (2021 and 2022) evaluated PFAS destruction in hazardous waste incineration. Achieved >99.99% destruction efficiency for multiple PFAS compounds. Residual PFAS detected in waste, but minimal emissions in stack gases. Study did not comprehensively address by product formation, particularly volatile non-polar compounds, leaving some slight uncertainties (WasteDive,2023).

Table 1. Examples of real world HWI studies

Source and Country	Temperature range noted	Description
Van Caneghem et al., 2025 , Belgium	1040°C in post combustion chamber, some areas potentially reaching higher	The study found that a hazardous waste incinerator was highly effective at destroying PFAS in contaminated soil, achieving a DRE between 99.999% and 99.999%. Flue gas emissions showed only a slight increase in PFAS levels during soil treatment, though the PFAS profile shifted, PFOA emerged as the dominant compound despite being minimal in the original soil. This indicates that other PFAS may thermally degrade into PFOA during incineration. While the findings support incineration as an effective treatment method for PFAS, the authors highlighted limitations in current analytical methods and emphasised the need for improved measurement techniques and clearer regulatory standards.
Veolia (2025), USA	1115°C and a residence time of 2.3 seconds.	Thermal treatment via high temperature incineration of PFAS in AFFF firefighting foam, contaminated soil, and spent carbon water treatment media. Achieved destruction efficiency over 99% of targeted PFAS, achieving up to 99.9999% destruction for PFOS and PFHxS. Most solid residues showed no detectable PFAS, with minimal levels detected near method limits in a few cases. Liquid residues had very low PFAS levels, below EPA drinking water limits. Air emissions demonstrated over 99% destruction efficiency with negligible by-products.
Martin et al., 2023 , USA	Not specified	Measured 35 soil samples collected near a hazardous waste incinerator. Detectable levels of PFBS, PFOS, PFOA, and GenX were found, ranging from 0.05 to 8.3 ng/g. The study concluded that while incineration removed a substantial portion of PFAS, incomplete combustion resulted in the formation of by-products
New York State Department of Environmental Conservation facilities (NY State, 2021), USA	Not specified	Study near Norlite hazardous waste combustor facility. Found no distinct PFAS aerial deposition pattern. PFAS detected at low levels in all soil samples but below NYSDEC guidance values, suggesting effective destruction.

4.6 PFAS Residues from Municipal Waste and Sewage Sludge Incineration

The amount of municipal waste being incinerated has grown rapidly across all parts of the UK over the past decade ([Smith and Bolton, 2025](#)). In England, 50% of municipal waste was incinerated in 2023-24.

PFAS are present in various products. When mixed waste is incinerated at MWIs, these substances may be unintentionally processed, complicating waste management and increasing the risk of incomplete destruction. Estimating PFAS content is complicated by the heterogeneity of municipal solid waste, analytical challenges, and the presence of precursors that are difficult to measure ([Weitz et al. 2024](#)).

The effectiveness of MWI in fully destroying PFAS has been considered in studies, with evidence suggesting that incomplete combustion may contribute to localised environmental contamination. While detected concentrations are normally low (in the ng/L range), findings indicate that PFAS breakdown may be incomplete under certain conditions. Some studies have identified residual PFAS in municipal waste incinerator (MWI) emissions, flue gas treatment residues, and surrounding environments. Findings include slightly elevated PFOA levels in air samples downwind of MWIs in China ([B. Wang et al., 2020](#)), PFAS in surface water and soil near incineration sites in the USA ([Hogue 2020](#)), and detectable levels in pine needles and mosses near European waste incinerators ([Arkenbout & Bouman 2021](#)). [Baptista and Perovich, 2019](#) notes that incinerators are frequently located in disadvantaged areas in the USA.

[Lemieux et al. \(2007\)](#) was one of the first studies to investigate PFAS emissions from MWI. The study targeted 14 perfluorinated compounds, including PFCAs (C₄–C₁₂), PFSA (C₄, C₆, C₈, C₁₀), and PFOSA, measured in exhaust gases from the incineration of carpet samples spiked with commercially available PFCs at 952 to 998°C. Most common compounds detected were PFHxA and PFOA (<1 µg/m³). Though contamination issues during sampling required further investigation.

Several further studies have since detected PFAS residues in bottom ash, fly ash, leachate, and wastewater from MWIs, highlighting ongoing challenges in achieving complete destruction ([Johansson et al., 2025](#); [Hyks et al., 2025](#); [Björklund et al. 2023](#); [Liu et al. 2021](#); [Strandberg et al. 2021](#); [Blasenbauer et al., 2020](#); [Chen et al., 2023](#); [RWS 2020](#); [Wohlin 2020](#); [Hyks and Hjelm 2023](#); [Björklund et al., 2024](#); [Jelinek et al., 2024](#)). Air emissions are the least studied, with only one study to date having measured flue gas concentrations from MWI ([Björklund et al., 2023](#)). As gaseous PFAS are difficult to quantify, most research has instead focused on analysing ash and condensate byproducts.

Temperature appears to play a major role in destruction efficiency, with [Solo-Gabriele et al., 2020](#) finding that higher incineration temperatures resulted in lower PFAS levels in

landfill leachates from municipal solid waste ash. However, it is unclear whether the reduction in PFAS levels in leachates was due to actual thermal destruction or the transformation of PFAS into volatile species. [Sandblom 2014](#) measured PFAS concentrations in bottom ash, fly ash, condensate, and wastewater from four Swedish waste incineration plants operating at ≥ 850 °C. Despite meeting EU regulatory standards and majority destruction of PFAAs, small amounts were detected in the ng/L range.

[Ministry of Environment of Denmark, 2024](#) highlights waste incineration is effective at destroying PFAS in waste, with emissions from waste and biosolids incineration generally low compared to other sources, except for some fluorine gases from incinerating fluoropolymers, where knowledge is lacking. While most studies report low PFAS concentrations in incinerator residues (ng/L) and ash ($\mu\text{g}/\text{kg}$) and good rate of PFAS destruction, they typically analyse only a limited subset of compounds, leaving the fate of many unmonitored PFAS unknown. The detection of even small quantities of PFAS in combustion gases and ash suggests that complete mineralisation is not always achieved. The lack of fluorine mass balance assessments may prevent definitive conclusions on destruction efficiency ([Smith et al., 2024](#)).

While PFAS residues have been detected near some incineration facilities, it is not known whether these originate from incinerator emissions or other sources. The widespread presence of PFAS in the environment from multiple sources complicates efforts to distinguish between background contamination and emissions from waste combustion. In addition, historical operation of waste incinerators may not reflect current best practice, meaning legacy emissions could still be detectable in soils ([Brunschwiler, 2023](#)). Insights from the thermal treatment of non-PFAS POPs, such as polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans could help refine PFAS incineration strategies ([Winchell et al., 2021](#)).

Studies on thermal treatment of wastewater treatment plants (WWTP) biosolids are lab-scale and may not be reflective of real-world conditions ([Winchell et al., 2021](#); [Kim et al., 2015](#)). Few studies have examined PFAS gaseous emissions from sewage biosolids incinerators, with most focusing instead on PFAS levels in biosolids ([Loganathan et al., 2007](#)). [Seay et al. 2024](#) found that a WWTP operating a sewage biosolids incinerator achieved an overall PFAS destruction efficiency of approximately 51%. [Zhao et al., 2023](#), highlighted that incinerating biosolids at $1,150$ °C can effectively break down PFAS, with longer gas residence times improving performance. [Urciuolo et al. 2025](#) investigated PFAS degradation in municipal biosolids using a lab-scale fluidized bed combustor at 850 °C. Incineration achieved 99.9% PFAS destruction, although trace amounts of PFBS, PFOS, and PFTeDA remained, mainly in ash, with minimal residues detected in flue gas. [Al-Badri, 2024](#) concluded that thermal treatment via combustion at temperatures 850 - 950 °C is an effective method to degrade PFAS in biosolids/sewage sludge. Again, PFAS destruction efficiency varies with operating conditions and PFAS ([INERIS, 2023](#)).

Although MWIs and sewage sludge incinerators can achieve destruction rates exceeding 99.9% for some PFAS, their typical operating temperatures (~ 850 °C) may be insufficient for complete mineralisation of all PFAS. Additionally, the destruction of PFAS and

associated HF formation observed during incineration of pure PFAS salts or fluoropolymers may differ significantly when incinerating biosolids. This is due to the more complex gas-phase chemistry in biosolids, which includes organic volatile compounds, trace metals, and permanent gases (e.g., CO/CO₂, H₂, and C₁–C₄ hydrocarbons). Additionally, biosolids typically contain low concentrations of PFAS but high levels of organic and mineral content, making it more difficult to track degradation intermediates and end-products during thermal treatment ([Hakeem et al., 2024](#)).

Alternatively, a pilot study at a Chemours facility in North Carolina tested a **thermal oxidiser** operating above 1,047 °C and reported >99.99% destruction efficiency for five PFAS compounds (including HFPO-DA). However, details on residence time and PIC formation were not provided ([Focus Environmental Inc, 2020](#); [J. Zhang et al., 2023](#)).

4.7 Industry Guidelines for PFAS Incineration

Industry guidelines and existing studies (some previously discussed) indicate that achieving high destruction efficiency/mineralisation for PFAS (non-polymer) in various waste streams requires incineration at 1,000 to 1,200°C with a minimum two second residence time, as summarised in **Table 2**. However, these industry recommendations are based on limited studies and earlier hazardous waste incineration protocols developed by the US EPA and international agencies ([US EPA, 2024](#)), where key operational factors such as turbulence, residence time, and catalytic interactions are not always well-defined ([Tsang et al., 1998](#); [Wang et al., 2022](#)).

Table 2. Examples of global industry guidelines **and literature reported** temperatures for destruction of PFAS in thermal oxidising processes ([Winchell et al., 2021](#))

Source	Temperature range noted	Description
Pancras et al. (2016)	>1,000°C	Complete PFOS degradation and best practice disposal routes for PFAS adsorption media are high temperature incineration at >1000°C.
Kucharzyk et al., (2017)	1000°C or greater	High temperature incineration is required to destroy PFAS adsorbed to spent granular activated carbon (GAC).
ECHA, 2023b	1100°C	Literature indicates that hazardous waste incinerators at temperatures of 1 100 °C are able to destroy PFASs at more than 99%.
US EPA (2019)	Suggested 1,000°C	The effectiveness of incineration to destroy PFAS compounds and the tendency for formation of fluorinated or mixed halogenated organic byproducts is not well understood
US EPA (2024)	~1100°C	HWI may effectively destroy PFAS and minimise PICs at temperatures ~1,100°C with sufficient mixing and residence time.
UNEP (2019)	1,100°C	Recommended parameters for hazardous waste incineration (2s residence time at 1,100°C) to handle PFOS waste.
ECCC and Health Canada, 2024	>1,000°C	PFAS may not fully degrade from incineration at temperatures below 1000°C, which may result in the formation of other volatile fluorinated compounds

Source	Temperature range noted	Description
Held and Reinhard, 2020	1,100°C	For high temperature combustion, temperatures > 1,100 °C and 2 seconds contact time are required.
Ross et al., (2018)	700–1,100°C	High temperatures are required for destruction of gas-phase PFAS
ITRC, (2023)	≥1,000°C	Thermal destruction process typically characterised by oxidation at temperatures in excess of 1,000°C
Garg et al., (2023)	>1000 °C	Thermal destruction involves the burning/mineralisation of PFAS at high temperatures
Klein and Holmes, (2022)	1,100°C	High temperature incineration (≥1,100°C) with residence times over 2 seconds recommended for PFOS waste destruction.
Shields et al. (2023)	1,090°C	Reported >99.99% PFAS destruction at >1,090°C. Below 1,000°C, volatile PFAS emissions increase.
Mattila, (2024)	>1100	PFAS degrade at 1,100°C with minimal PIC formation. At ~800°C, short chain PFAS form. Some PFAS may persist in furnace systems during temperature fluctuations.
Weitz et al. (2024)	>850°C	Review of 7 lab studies and 18 pilot scale facilities concluded that systems operating above 850°C could achieve ~99.99% for certain PFAS destruction, depending on combustor design and operational parameters. Improved monitoring of PFAS related PICs needed.
Schultz et al. (2003)	1,200°C	Review of industrial scale experiments confirmed PFAS saturated activated carbon is effectively destroyed at 1,200°C (2s residence time) and the exhaust gas could be scrubbed to produce a solid CaF ₂ precipitate

Source

**Temperature
range noted**

Description

[Blotevogel et al. \(2024\)](#)

≥1,000°C

bis-FASIs begin degrading at 600°C but mineralisation starts to occur at >900°C. HWIs at ≥1,000°C can achieve full mineralisation if all process conditions are optimised.

4.8 Conclusions on Incineration

HTI remains the most widely used method for large scale PFAS disposal, preventing accumulation in landfills and recycling systems. Regardless of high costs and energy demands, HTI is the only commercially viable technology capable of treating PFAS contaminated waste at scale.

The evidence found in our review indicates that achieving near complete PFAS mineralisation and PFAS destruction efficiencies of >99.99% for PFAS firefighting foams can be achieved at 1,100 °C, with a two second residence time in the secondary combustion chamber, along with sufficient turbulence, and properly balanced stoichiometry (waste, fuel, oxygen, and gas-phase components). Additional assessments, such as evaluating trailing temperatures at 1,000 °C, in real-world hazardous waste incinerators, may necessitate revisions to these conclusions.

While many PFAS begin to decompose or enter gas phase by temperatures ~700 °C, non-polymer PFAAs (including PFOS and PFOA) and other perfluoroalkyl compounds likely require higher temperatures for complete mineralisation. Fully fluorinated short-chain PFCs, such as CF₄ and C₂F₆, are even more stable and often persist as PICs, with CF₄ requiring temperatures above 1,100 °C for mineralisation. Nonetheless, noteworthy degradation of both compounds has been observed at 1,100 °C. PTFE (Teflon), the most thermally stable fluoropolymer, is thermally degraded completely around 800-850 °C. However, complete polymer mineralisation also depends on sufficient turbulence and residence time to minimise PIC formation.

The main challenge in effective PFAS destruction lies in preventing or breaking down highly volatile PICs formed during the process. This requires sustained high temperatures and optimised process conditions. Incinerators operating at lower temperatures, with shorter residence times, or under fluctuating conditions may fail to fully mineralise PFAS. This can lead to the formation and accumulation of PICs, which may persist in emissions and residual ash due to incomplete degradation and some of which have high global warming potentials. These by-products, though often present in low concentrations, are difficult to detect and may pose long term environmental risks. Reliable prediction of which PICs form under suboptimal conditions or in what quantities is not yet possible. Additionally, many evaluations have only assessed liquid-fired materials at pilot scale, with less comparative PIC studies on solid or containerised wastes.

Hazardous waste incinerators and cement kilns can reach temperatures above 1,100 °C, making them suitable for PFAS mineralisation. In contrast, municipal waste incinerators and sewage sludge incinerators typically operate at lower temperatures (~850 °C), which may achieve 99.9% destruction efficiencies of certain PFAS, but are unlikely to ensure complete mineralisation and prevent PICs across the full spectrum of PFAS.

Advanced exhaust gas treatment systems are necessary for capturing and neutralising harmful emissions, yet their effectiveness in trapping PFAS and degradation by-products remains uncertain. Also, residual ash may contain inorganic fluoride and PFAS bound to calcium, while HF, a highly toxic and corrosive gas, also requires careful management. Even with advancements, uncertainties remain regarding incineration efficiency due to several key factors:

1. Variability in operating conditions: HTI efficiency is influenced by multiple technical and operational factors. Temperature recommendations for PFAS destruction vary widely, from 650°C to over 1,400°C, depending on waste type and PFAS stability, though at 1,100°C, residual by-products are expected to be typically minimal. Combustion efficiency is further impacted by temperature fluctuations, turbulence, oxygen levels, water, hydrogen donors, PFAS ratio, catalysts, additives, flame radicals, and residence time, all of which require further study to confirm consistent and complete mineralisation.

2. Incomplete Measurement Methodologies: Most studies only assess a limited subset of PFAS, such as PFOA and PFOS, often neglecting key by-products, which can lead to underestimated emissions and an inaccurate assessment of overall destruction efficiency. The structural diversity of PFAS complicates detection, characterisation, and quantification. Current analytical techniques detect only a fraction of PFAS, and non-standardised sampling methods possibly result in inconsistent emissions data and uncertainty regarding volatile by-product capture, hindering cross study comparisons. Additionally, some of these analytical techniques are relatively new and remain under development. Fluorine mass balance assessments are important for understanding how fluorine from PFAS decomposes and where it accumulates whether in gas emissions, captured waste, or residual ash. Yet output fluorine may be distributed across undegraded PFAS, HF, PICs, other chemical species, scrubber wastewater, or reactor surfaces, many of which remain insufficiently measured. Therefore, the large number of PFAS compounds, their presence in mixed waste streams, and their partitioning across multiple phases make completing a full fluorine balance highly challenging. Establishing universal protocols for measuring PFAS destruction efficiency in residues would be beneficial to ensure reliable and comparable data.

Although, implementing reliable sampling and analysis in operational facilities presents practical challenges. As these facilities typically process large volumes of different wastes, logistical challenges such as sample collection, storage, and preparation complicate analysis. Typically, only gram scale samples are analysed, which may not adequately represent the much larger volumes of waste treated. In addition, accurately quantifying fluorinated emissions may require detailed knowledge of the PFAS content in the waste being incinerated. Obtaining this information is challenging. However, such data could improve the reliability of fluorine mass balance assessments and reduce the risk of underestimating emissions. Also, enhanced air quality monitoring and soil/water contamination assessments near incineration sites could provide valuable insights.

3. Diverse Waste Matrices: Different complex waste streams, such as soils, AFFF, sewage biosolids, landfill leachates, and municipal solid waste, introduce additional

variability in PFAS decomposition and emissions. Knowledge on the content of PFAS in solid or mixed PFAS containing waste remains limited and requires further investigation.

4. Uncertain Thermal Decomposition Pathways: PFAS breakdown mechanisms remain poorly understood, particularly regarding PIC formation. Gaps include the influence of PFAS headgroup and chain length, the role of radical intermediates in destruction and recombination, and the underlying processes and kinetic bottlenecks in complex wastes such as soil and AFFF. Joint experimental and computational studies are needed to clarify PFAS decomposition pathways under high-temperature oxidising conditions. Experimental work should use comprehensive analytical techniques to determine fluorine sinks and mass balances, while computational studies can support mechanism development.

5. Laboratory vs. Real World Conditions: Current research on emissions of fluorinated organic compounds is limited, preventing definitive conclusions, but future real-world studies are expected to inform and revise current understandings. Most incineration studies are conducted at the laboratory scale, failing to replicate real world variability in waste composition, moisture content, calorific value, and temperature distribution. For example, large scale systems are less homogeneous, making it harder to achieve consistent parameters such as temperature and oxygen levels, which affects the representativeness of laboratory results. Also, inconsistent terminology, such as destruction, mineralisation, and elimination, complicates assessments of incineration effectiveness in studies. Field scale studies to assess real world destruction efficiencies, emissions variability, and operational constraints in full scale facilities would provide additional useful data. High destruction efficiencies indicate parent PFAS reduction but may not guarantee full mineralisation, as PIC formation may be overlooked, limiting fluorine mass balance and risking unaccounted environmental emissions.

6. Inconsistent Air Pollution Control Technologies: Variations in incinerator designs and air pollution control systems lead to variability in emissions and uncertainty on percentage capture of volatile by-products. Removal efficiency varies among PFAS types. There is an absence of requirements mandating the capture of these compounds, particularly for next generation PFAS, for which risks to the environment and human health are less well studied or unknown. Standardised detection and measurement protocols are helpful for accurately assessing destruction efficiency and emissions, while improved flue gas treatment can help minimise the release of these harmful by-products.

While 100% thermal destruction of PFAS during waste incineration is difficult, evidence shows that HTI can achieve near complete mineralisation under optimal conditions and remains one of the few practical options for managing large volumes of PFAS-containing waste. However, its long-term role may be limited by high energy demands, technical constraints, environmental uncertainties and its carbon footprint. Ensuring safe and effective PFAS management will require further full-scale testing, improved measurement methods, and a deeper understanding of PIC formation, alongside the development of sustainable, scalable, and cost-effective alternatives. Progress will depend on coordinated action across academia, government, and industry.

5. Comparative Analysis of PFAS Remediation Methods for solids and liquids

The strength of the C-F bond and low surface energy makes conventional remediation methods for soil and groundwater largely ineffective, requiring advanced technologies designed to overcome PFAS's chemical resilience ([Vargette et al., 2023](#)). Unlike volatile organic compounds (VOCs), which are often treated using standard approaches, PFAS remediation is far more complex, especially at sites with co-contaminants. The need to meet increasingly stringent standards, often below ng/L levels, adds to the challenge ([Geosyntec, 2024](#)). Soils and groundwater can act as both sinks and sources of PFAS, with groundwater particularly important as it provides a source of drinking water. Contamination can also affect surface waters and engineered materials such as capping layers, paving, and drainage systems. The behaviour of PFAS in liquids and solids differs, necessitating tailored remediation approaches for each. Nevertheless, several technologies capable of immobilising, removing, or destroying PFAS in liquids (drinking water, firefighting foam, landfill leachate etc) and solids (soil, sludge etc) have advanced from lab research to pilot and full-scale applications in the UK and Europe ([Nathanail et al., 2024](#)).

PFAS remediation approaches fall into four main categories:

1. **Separation and Concentration Techniques:** PFAS are extracted and concentrated into a smaller waste volume (e.g. foam fractionation).
2. **Destructive Technologies:** Break down PFAS chemically, with HTI being a common method.
3. **Adsorption Approaches:** Bind PFAS within a medium to prevent release (e.g. GAC).
4. **Integrated or Combined Technologies:** Hybrid approaches that combine separation, immobilisation, and destruction for improved efficiency.

Broadly, methods are classed as **sequestration** (separate and concentrate PFAS in or on a media but requiring ongoing waste management) or **destruction** (breaking C–F bonds for permanent removal). While destruction minimises long term waste, it is energy intensive, requires harsh reaction conditions, long treatment times, is costly, and technically complex, making it more suitable for smaller concentrated volumes ([Ng et al., 2021](#)). Therefore, many remain at low to intermediate technology readiness levels.

Remediation can be carried out directly at the contamination site (*in situ*), for example by treating water using GAC. Alternatively, contaminated material can be removed and treated or disposed of at a separate facility (*ex situ*) i.e HTI. *In-situ* approaches tend to involve fewer transport requirements and are generally less complex to manage, but in some situations, *ex-situ* treatment is needed to limit the risk of further PFAS spread ([Toolan & Wentworth, 2025](#)). Groundwater remediation normally relies on extraction and *ex-situ* treatment. To date, no *in situ* technology has been proven cost effective and

energy efficient for complete PFAS destruction in soil and groundwater, and no single method has demonstrated long term sustainability across all site conditions.

Effective PFAS destruction requires strong evidence of complete mineralisation, especially for short chain PFAS, precursors and non-precursors. This includes conducting fluorine mass balance assessments and using both targeted and non-targeted analyses to confirm complete PFAS mineralisation ([Harding-Marjanovic et al., 2015](#)). Without such analysis, undetected or transformed PFAS compounds could undermine remediation success. Other important parameters include economic viability (process and overall remediation costs) and sustainability (including duration, energy consumption, and CO₂ emissions), which are often poorly documented ([Held and Reinhard, 2020](#)). These knowledge gaps can hinder thorough evaluation of new and existing technologies.

Scientific progress, regulatory momentum, and market interest are driving rapid development of PFAS treatment options, particularly those aimed at destruction ([Bowles et al., 2024](#)). Yet, few can destroy PFAS-contaminated waste in both liquid and solid phases. This is important because many technologies presented as alternatives to incineration for solid PFAS wastes, would in practice require an additional step to transfer PFAS into the liquid phase before treatment. Therefore, most field and industrial applications continue to rely on sequestration due to its relatively low cost, operational simplicity, and ability to manage large volumes ([Geosyntec, 2024](#)). Nevertheless, the PFAS-containing residues still requires further treatment, which may cause environmental impacts from resource use and emissions at the treatment facility.

This review outlines the strengths and limitations of current approaches and highlights the need for cost effective, scalable, and sustainable solutions. Continued research and investment are needed to improve treatment performance, support regulatory compliance, and confirm lasting environmental protection. While this review covers a range of PFAS treatment technologies, new methods are continually emerging, many still limited to early-stage laboratory and pilot stage. In turn, this review cannot capture every technology currently under development.

Tables 3 to 5 provide Technology Readiness Levels (TRLs) as a framework to assess the maturity of remediation methods from early research (TRL 1–3), through development and validation (TRL 4–6), to demonstration and market readiness (TRL 7–9). These rough ratings for this report have been based on and supported by scientific literature as well as public and internal reports. For a deeper understanding of specific technologies discussed, additional resources offer more detailed insights ([ITRC, 2023](#); [Concawe et al., 2024](#); [Yadav et al., 2022](#); [Meegoda et al., 2022](#); [Sanzana et al., 2025](#); [Amen et al., 2023](#); [Verma et al., 2023](#); [Mahinroosta & Senevirathna 2020](#); [Riegel et al., 2020](#); [US EPA, 2022d](#)).

It is important to note that the technologies and approaches referenced in this review, including any mention of commercially available products and systems, are presented solely for information purposes. Their inclusion does not imply endorsement or recommendation by the Environment Agency.

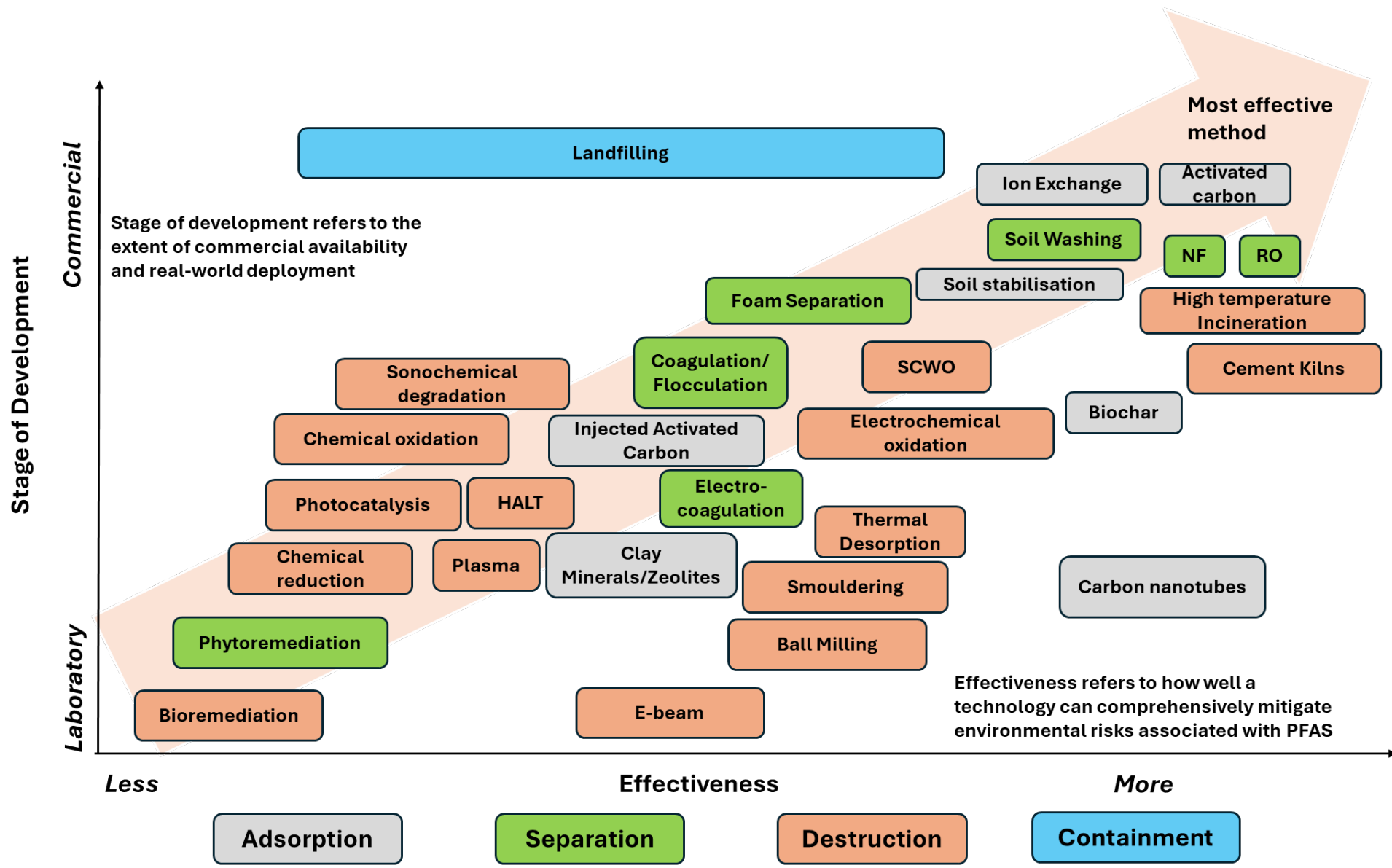


Figure 8. Rough comparison of key PFAS remediation technologies for soil and water by potential effectiveness, commercial maturity, and availability adapted from [Concawe et al., 2024](#) (please note not to exact scale and some technologies not included).

5.1 Full Scale Solid PFAS Remediation Methods

This section reviews full scale remediation methods for PFAS in solid materials. Incineration, covered in earlier sections of this report, is excluded from this discussion. Table 3 summarises the key advantages, limitations, and efficiencies of these methods ([Mahinroosta & Senevirathna 2020](#); [Geosyntec, 2024](#); [Concawe et al., 2024](#)).

5.1.1 Landfill and Offshore Disposal

PFAS emissions occur throughout their entire lifecycle, and some will end up in waste streams. Landfilling remains a widely used disposal method for PFAS contaminated soils and solid containing waste, providing a short-term solution against groundwater contamination while complementing other remediation strategies. Modern engineered landfills are designed with liners, leachate drainage, and gas extraction systems to minimise PFAS migration. However, older landfills (pre-2001), constructed with lower engineering standards, may pose a higher risk of contaminant discharge through the base, sidewalls, and surface, increasing the potential for environmental contamination ([ECCC and Health Canada, 2024](#)). In England, there are nearly 20,000 historic landfills and around 1,800 permitted (operational and closed) landfills ([Toolan & Wentworth, 2025](#); [Environment Agency, 2024](#); [2025](#)).

Studies worldwide, including England, have consistently detected PFAS, particularly PFAAs, in non-hazardous landfill leachate, highlighting questions over their long-term persistence ([Ross et al., 2018](#); [Fuentes et al., 2017](#); [Gobelius et al., 2018](#); [Solo-Gabriele et al., 2020](#); [US EPA, 2024](#); [Tian et al., 2018](#)). Some PFAS in leachate may also diffuse through some types of landfill liners ([Rowe et al., 2023](#)). A recent UK study [Defra et al., 2024](#) provides evidence of PFAS contamination, detecting PFAS in all 35 leachate samples from 24 operational, closed, and historical landfills at concentrations ranging from 1.04 to 107 µg/L (median: 14 µg/L). The most dominant compounds, accounting for 85–90% of total PFAS were PFOA, PFHxA, 5:3 FTCA, PFBA and PFBS. PFAS in landfill leachate may pose long-term environmental risks, potentially persisting beyond the operational lifespan of landfills, leading to delayed emissions once environmental conditions change ([Propp et al., 2021](#)).

Where non-hazardous landfill leachate (raw and treated) is discharged to wastewater treatment plants (WwTP), it may undergo further treatment. However, there are significant technical challenges to removing PFAS from wastewater. Therefore, any PFAS released to the wastewater system can either enter surface waters directly or accumulate in biosolids applied to land ([Lenka et al., 2021](#)). During treatment, precursor compounds may also be transformed into PFAAs. Leachate may additionally be directly discharged to controlled groundwater/surface water from leachate treatment plants (LTP) with discharge consents. LTPs are not typically designed to treat PFAS compounds. Although landfill leachate can contain elevated concentrations of PFAS, its overall contribution to WwTPs

final effluent is typically limited due to the relatively low volumes involved. [Wei, Xu, and Zhao \(2019\)](#) reviews PFAS treatment technologies for landfill leachate.

In response, the Environment Agency is reviewing restrictions on PFAS-containing waste across all landfill types, with soils currently making up a significant proportion of landfill inputs. Studies also suggest PFAS may also be present in landfill gas emissions, requiring further investigation ([Ahrens et al., 2011](#); [Lin et al., 2024](#); [Tolaymat et al., 2023](#)). To address this, the Environment agency is also planning further studies on PFAS releases via landfill gas. Similarly, the US EPA has also published some preliminary studies ([US EPA, 2024b](#)).

Regulatory developments have driven the growth of pre-treatment methods, such as stabilisation, to improve compliance. However, limited hazardous waste landfill capacity and space constraints may pose challenges. While landfilling remains cost effective for small waste volumes, its low costs may deter investment in more sustainable treatment technologies. Long-term environmental liabilities associated with PFAS presence in landfills must be considered, as they can potentially become sources of contamination ([Environment Agency, 2021](#)). Although waste containing PFAS that does not contain POPs is defined as non-hazardous and can legally be disposed of in any landfill, this is not the preferred option. HTI and full mineralisation remain the recommended approach.

Offshore disposal has been explored as a potential alternative to isolate PFAS waste in marine environments, reducing its impact on land-based disposal systems. However, this approach presents challenges, including regulatory barriers, transportation risks, and the risk of potential effects on marine ecosystems. Ensuring the effectiveness of offshore disposal would require extensive environmental assessments and long-term monitoring. As such, it is not considered a safe or sustainable method.

5.1.2 Sorption and Stabilisation

Sorption and stabilisation technologies immobilise PFAS in soils and sediments by using chemical amendments or sorbents that reduce leaching by effectively locking up the PFAS. These methods are relatively quick, simple, and cost effective, with successful applications in laboratory studies, pilot projects, and some full-scale implementations under both *in situ* and *ex situ* conditions. Amendments such as activated carbon, resins, minerals, biomaterials, modified clays, and composites have demonstrated varying degrees of effectiveness ([Das et al., 2013](#); [ITRC, 2023](#); [Hale et al., 2017](#); [Navarro et al., 2023](#)). Delivery methods such as injection or *in situ* mixing can produce different outcomes depending on site geology and treatment objectives. Solidification with cement can be integrated to reduce leaching and improve soil strength. Overall, adsorption technologies are effective for certain PFAS but have limitations. Short chain PFAS, due to their high solubility, are less likely to be effectively adsorbed and require long term efficacy. Also, adsorption is only a temporary solution, as the media can degrade over time, potentially becoming a secondary source of contamination and requiring robust monitoring. Proper management and disposal of spent adsorption media is necessary to prevent further environmental release. While these technologies show potential to be pragmatic scalable

approaches, site specific optimisation is often necessary to achieve the desired performance. Though, ongoing work and long-term monitoring are underway ([Darlington et al., 2018](#), [Bräunig et al; 2021](#); [McDonough et al., 2022](#); [Mahinroosta & Senevirathna 2020](#)).

5.1.3 Soil Washing

Soil washing is an *ex situ* remediation technique that removes PFAS from contaminated soils by transferring them into the liquid phase for further treatment or disposal. Water is typically the primary extracting agent, with surfactants, organic solvents, or pH adjustments possibly enhancing PFAS solubility and desorption. However, PFAS retention in soils is influenced by hydrophobic and electrostatic interactions, and soil, organic carbon content, pH, and the presence of organic matter ([Higgins et al., 2006](#)). A higher soil organic carbon content increases PFAS sorption. Longer chain PFAS more readily adsorb onto soil particles ([Shahsavari et al., 2021](#)), making removal more challenging and often requiring better extraction techniques.

Soil washing is effective for granular soils but less efficient for fine grained, clay rich soils, where PFAS bind strongly to fine particles, increasing treatment complexity and costs. Large scale cleanups at military and industrial sites have also demonstrated high removal rates in coarse soils, though effectiveness varies with soil composition ([ITRC, 2023](#); [Geosyntec, 2024](#); [Wei et al; 2017](#)).

However, the process generates a concentrated waste stream, including fines and process water, which may require additional treatment through HTI, to guarantee complete PFAS removal. Proper management of these waste streams is necessary to prevent secondary contamination and ensure long-term sustainability. Compared to thermal methods, soil washing is largely more energy efficient, cost effective, and allows for the reuse of cleaned sand and gravel fractions. Regulatory acceptance of the technology is increasing, with modular and mobile units now available for smaller or remote sites. While enhancements such as surfactants and pH adjustments have shown promise in improving performance, further research and development is needed to optimise soil washing parameters, particularly for fine grained soils and overall cost effectiveness ([Grimison et al., 2023](#); [Quinnan et al., 2022](#))

5.1.4 Cement Kilns

Cement kilns offer a HTI solution for PFAS destruction, achieving >99.999% efficiency in controlled trials. Originally used for treating polychlorinated biphenyls (PCBs) and high fluorine content spent pot linings, they can integrate PFAS disposal into existing industrial infrastructure with minimal modifications, enhancing both energy efficiency and sustainability. It has been shown that operating cement kilns at approximately >1,200 to 1800°C with extended residence times can effectively degrade PFAS. Additionally, the co-incineration of calcium-containing minerals facilitates the formation of calcium fluoride (CaF₂), a stable by-product that reduces gaseous fluorinated emissions and improves environmental outcomes ([Klein and Holmes, 2022b](#)). Laboratory studies indicate that

calcium species promote mineralisation of PFAS waste at relatively low temperatures (400-800°C) ([Wang et al., 2013, 2011](#); [Riedel et al., 2021](#)). Cement kilns have also been used to incinerate PFAS saturated ion exchange ([Patterson, 2020](#)) and destruction efficiencies above 99.99% for chlorofluorocarbons and decaBDE have been reported ([Ueno et al., 1997](#); [Yang et al., 2012](#)).

Trials conducted in Queensland, Australia, between 2016–2017 demonstrated destruction efficiencies of 99.999% for PFOS, PFOA, and PFHxS in both liquid and solid PFAS waste. Since then, Cement Australia (Geocycle) has adopted these treatment processes at its Gladstone and Railton facilities to treat PFAS contaminated materials, including AFFF concentrate ([Concawe et al., 2024](#); [Klein and Holmes, 2022](#)). Interim guidance published by the US EPA in April 2024, also suggests conditions in cement kilns e.g., $\geq 1,650^{\circ}\text{C}$, long gas phase residence time (4 to ≤ 16 seconds in long kilns) may effectively treat PFAS waste ([HSE, 2025](#)). This approach is now also recognised in the Basel Convention General technical guidelines on environmentally sound waste management ([UNEP](#)).

While cement kilns effectively destroy high concentration waste, due to possible limited capacity they may be suited for low volume high concentration waste streams. A 2023 biomonitoring study by [ToxicoWatch](#) detected PFAS in eggs of chickens, surface water, and sediment within 2.5 km of a cement kiln in the Košice Region, indicating potential localised contamination that warrants further investigation.

Despite its potential effectiveness, the broader adoption of cement kilns for PFAS destruction does face some challenges. In England, there are no kilns currently licensed to accept PFAS waste and few globally are approved to handle PFAS containing solids leading to increased transport and handling costs. The risk of incomplete PFAS breakdown in lower temperature zones may necessitate additional gas treatment measures. Although virtually all organic compounds can be destroyed at 1400°C and calcium-assisted breakdown may reduce the temperatures required for effective destruction.

Operational costs may vary widely, and limited vendor transparency, making cost assessments challenging. In addition, limited emissions monitoring raises questions about the potential formation of PICs, highlighting the need for further assessment ([Concawe et al., 2024](#)). To support regulatory acceptance and demonstrate effective treatment, a range of evidence is likely to be needed. This includes confirmation that the kiln is operating under appropriate conditions, that permits are in place, and that waste materials are properly tracked and documented. Where possible, additional assurance can be provided through stack emission data via OTM-50 ([Concawe et al., 2024](#)). Furthermore, there may be other potential barriers, such as the willingness of the kiln operators to take the material (given the cost and permitting implications), public perception of a cement kiln burning PFAS, the implications for the cement product and the opinion of their customers ([HSE, 2025](#)). However, they may serve as a promising final disposal option for specific PFAS contaminated materials such as firefighting foams/soil or as part of a treatment train, particularly in cases where other treatment options are impractical or not available.

Table 3. Outlines solid treatment remediation methods implemented at full scale and under real world conditions for PFAS remediation.

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
Excavation and Landfill Technology readiness level (TRL) 9	Effective for localised contamination; can remove "hot spots"	Physical removal and transport to licensed landfill facilities	<ul style="list-style-type: none"> - Well-established method - Immediate reduction of exposure risk - Effective for highly contaminated areas - Effective whole PFAS class - Simple operation with established regulatory frameworks. 	<ul style="list-style-type: none"> - PFAS persistence in landfills creates long-term liability risks - Potential release via leachate (e.g., short-chain PFAAs) into groundwater or biosolids - Potential limited hazardous waste landfill capacity and lack of new space development - Requires thorough landfill design, leachate management, transport and stabilisation. -Current leachate management difficult -Liner leaks and volatile PFAS in landfill gas require more research 	<ul style="list-style-type: none"> - Remediation of "hot spots" with high PFAS concentrations - Treatment of contaminated soils, sediments, and crushed concrete
Offshore Disposal Technology readiness level (TRL) 6 limited adoption	Minimises terrestrial impacts but effectiveness varies. However, it is not a suitable method	Isolation of contaminants into marine environments	<ul style="list-style-type: none"> - Reduces land use impacts - Suitable for large-scale contamination 	<ul style="list-style-type: none"> - Regulatory and logistical challenges - Marine ecosystem impacts - Requires rigorous monitoring 	<ul style="list-style-type: none"> - Large-scale contamination where land disposal is impractical.

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
<p>Sorption and Stabilisation Technologies</p> <p>Technology readiness level 8</p>	<p>Good reduction in long chain PFAS leaching. Removal efficiency varies depending on the type of amendment and the specific PFAS being targeted</p>	<p>Adds amendments (e.g., activated carbon, resins, clay-based materials) to soil to enhance PFAS adsorption and reduce leaching through electrostatic and hydrophobic interactions</p>	<ul style="list-style-type: none"> - Quick and simple to implement with good PFAS reduction - Low cost compared thermal treatment and commercially available - Versatile for both <i>in situ</i> and <i>ex situ</i> applications - Generally low mass of stabiliser needed & many available 	<ul style="list-style-type: none"> - Non-destructive - Long-term effectiveness uncertain. - Extensive work on site. - Performance depends on site-specific factors such as soil characteristics and PFAS types - May need reapplication 	<ul style="list-style-type: none"> - AFFF-impacted soils - Clay-based and composite materials for reactive barriers and stabilisation.
<p>Soil Washing</p> <p>Technology readiness level 7-8</p>	<p>Effective for granular soils and still fairly effective for clay/fine soils. Broadly effective across PFAS class</p>	<p>Uses an extracting agent (e.g., water, surfactants, solvents) to desorb PFAS from soil into a liquid phase for</p>	<ul style="list-style-type: none"> - High removal efficiency for sandy soils and can remove other contaminants - Surfactants/solvents enhance desorption - Soil can be reused after washing <i>in situ</i> no need transport soil 	<ul style="list-style-type: none"> - Lower efficiency and higher costs for fine soils and high organic content. - Requires further development for large-scale application as requires substantial water and large machinery - Uncertainties regarding effectiveness/results, especially <i>in</i> 	<ul style="list-style-type: none"> - Bench-scale and field trials at USA military sites - High removal rates demonstrated in controlled settings

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
		further treatment or disposal	-Technically mature and commercially available	<i>situ.</i> -Less suited for cohesive soils and concrete -Future improvements needed i.e large volumes of PFAS impacted water, may require co-solvent or surfactant. -Need to manage the wash water	
Cement Kilns Technology readiness level 8	>99.999% (controlled trials)	HTI at ~1,200 to 1,600°C; co-incineration with calcium minerals forms CaF ₂ , limiting gaseous fluorinated emissions.	-Integrates into existing infrastructure with minimal modifications -Effective for both liquid and solid PFAS waste; energy-efficient compared to incineration - Produces stable by-products (CaF ₂) can reduce emissions - Demonstrated success in trials with >99.999% destruction of PFOS, PFOA, and PFHxS.	-Few kilns globally are licensed for PFAS waste, increasing transport and disposal costs - Incomplete destruction risk in lower-temperature zones - Limited emissions monitoring and potential PIC formation -Logistics of taking PFAS waste	- Low-volume, high-concentration PFAS waste i.e AFFF concentrate disposal; potential for broader use with improved emissions control and process efficiency - However, no cement kiln is currently permitted for PFAS waste in England

5.2 Full Scale Liquid PFAS Remediation Methods

This section presents full scale liquid remediation methods successfully implemented for PFAS removal under real world conditions ([Geosyntec, 2024](#); [ITRC, 2023](#); [Merino et al., 2016](#)). Table 4 provides a summary of these methods, outlining treatment types, advantages, limitations, and efficiencies. At present, sequestration remains the dominant approach for effectively removing PFAS from water ([Ross et al., 2018](#)).

5.2.1 Granular Activated Carbon (GAC)

GAC is a widely used water treatment technology at full scale, known for its large surface area, strong adsorption capabilities, and affinity for oil, which enable the effective removal of organic compounds. Derived from materials such as wood, coconut shells, or coal, GAC is particularly effective in adsorbing long chain PFAS, including PFOA and PFOS. PFAS adsorption onto GAC primarily depends on their hydrophobicity, but several other factors, including pH, ionic strength, temperature, electrostatic interactions, organic content, and the specific chemical structure of PFAS, also influence performance ([Hansen et al., 2010](#); [Qian et al., 2017](#); [US EPA, 2024c](#)).

GAC has been successfully implemented in large scale applications, such as military installations and drinking water treatment facilities. Demonstrating its effectiveness in removing PFAS from contaminated water sources and reducing concentrations to levels compliant with regulatory standards ([US EPA, 2024](#); [Olsavsky et al., 2020](#); [Busch et al., 2010](#)). Studies have shown that GAC, used in successive filter beds, can achieve over 99.9% removal rates for certain PFAS in AFFF contaminated water ([Szabo et al., 2017](#)). However, this result was measured after only a short period of use. Additionally, powdered activated carbon (<0.1mm diameter) can be used for the removal of PFAS ([Pan et al., 2016](#)). Even though it is highly effective for PFOS/PFOA (>90%), GAC has limitations. It is less efficient at removing short chain PFAS (<6 carbons), such as perfluorobutane sulfonic acid (PFBS) and perfluorobutanoic Acid (PFBA), which have lower carbon adsorption affinity (often <50% to 99%), requiring more frequent regeneration or replacement, increasing operational costs.

Field data show adsorption capacities for PFAS are much lower than for other organic contaminants. Moreover, the introduction of long-chain PFAS to GAC already saturated with short-chain PFAS may cause the short-chain compounds to desorb ([Zhang et al., 2023b](#)). In complex matrices like AFFF contaminated water, pre-treatment may often be necessary to prevent fouling and maintain efficiency ([Appleman et al., 2013](#); [Medina et al., 2022](#); [Najm et al., 2021](#)). Continuous monitoring is needed to detect PFAS breakthrough and confirm sustained system performance.

GAC is typically used in packed bed flow through vessels arranged in series, where PFAS breakthrough is monitored through sample testing. Once breakthrough occurs, the spent

GAC is replaced with fresh media to maintain treatment effectiveness ([Franke et al., 2019a](#)). Proper disposal of spent GAC is important to prevent environmental contamination. GAC disposal options include HTI and landfilling both of which carry the risk of releasing PFAS back into the environment. Reactivation for reuse offers a more sustainable alternative, significantly reducing the carbon footprint while extending the service life of the material. However thermal treatment may compromise the adsorbent's structural integrity ([Vakili et al., 2024](#); [EPA, 2018](#)) and although thermal reactivation can destroy >99.9% of PFAS and recover most of the carbon, uncertainties remain around complete mineralisation and PICs ([Section 4.4](#)).

In short, GAC remains a widely used and effective technology for removing long chain PFAS due to its low energy and maintenance needs. However, it is less effective in removing short chain variants. Specialised GAC products designed for PFAS removal in different media are available. The success of GAC based treatment depends on appropriate system design, influent PFAS composition, co-contaminants, empty bed contact time, continuous monitoring, and responsible disposal practices to prevent secondary PFAS contamination ([Riegel et al., 2020](#)).

5.2.2 Ion Exchange Resins (IX)

IX resins are a well-established technology for removing PFAS from contaminated water, primarily through adsorption and electrostatic attraction. These resins are made from highly porous, water insoluble polymeric materials. There are two broad categories: cationic and anionic resins. Positively charged anion exchange resins are particularly effective in removing commonly targeted PFAS, such as PFOA and PFOS, which predominantly exist as anions under typical environmental conditions. The strong interaction between the negatively charged head of anionic PFAS and the positively charged resin sites enhances removal efficiency, while non anionic PFAS can also be captured through hydrophobic interactions ([Woodard et al., 2017](#); [Carter and Farrell, 2010](#); [Bolan et al., 2021](#)).

IX resins are available in two primary forms: single use and regenerable. Single use resins, which typically have a higher removal capacity, are disposed of after saturation ([Boyer et al., 2021](#)). They are the most common full-scale application today and can achieve >99% removal of both long- and short-chain PFAS when influent is relatively clean. Whereas, regenerable resins are restored on site using organic solvents, generating a concentrated PFAS laden brine that requires further treatment ([ITRC, 2023](#)). Performance depends on PFAS concentration and water matrix composition ([Zaggia et al., 2016](#)). Field studies have shown IX resins to be particularly effective in removing sulfonate containing PFAS, though short chain compounds tend to break through more quickly due to their lower affinity for the resin ([McCleaf et al., 2017](#); [Zeng et al., 2020](#)).

Compared to GAC, IX resins generally offer higher efficiency for removing short chain PFAS, require shorter empty bed contact times, higher PFAS capacity, and have a longer operational lifespan, albeit with higher initial costs ([Dixit et al., 2019](#); [Murray et al., 2021](#)). Although, dissolved organic carbon and co contaminants can reduce resin effectiveness,

often necessitating pre-treatment. Traditional regeneration methods using acids and alkalis are often inadequate for fully eluting PFAS, whereas organic solvents such as methanol or ethanol have shown greater efficacy ([Riegel et al., 2020](#)). IX can be integrated with electrochemical, hydrothermal, sonolysis, plasma and other methods ([Hussain et al., 2025](#)). While IX resins provide an effective alternative to GAC, particularly for short-chain PFAS, improvements in regeneration techniques and waste management may be needed to enhance environmental sustainability. However, both GAC and IX are widely used and effective technologies, reducing PFAS levels to below detection limits, and will likely continue to be industry standards for PFAS removal from water due to their ability to achieve high effluent water quality and concentrate large volumes effectively ([Ling et al., 2025](#)).

5.2.3 Reverse Osmosis (RO)

RO is an established method for removing PFAS from water. It employs semi-permeable dense membranes (pore sizes <1 nm) that allow water molecules to pass under pressure while retaining PFAS and other contaminants for disposal. RO is particularly effective for long chain PFAS, such as PFOA and PFOS, achieving removal efficiencies between 90% and 99% ([Liu et al., 2022](#); [Kucharzyk et al., 2017](#); [Thompson et al., 2011](#); [Riegel et al., 2020](#)). The efficiency of RO depends on several factors, including solute concentration, operating pressure, water flux rate, and membrane type. Tighter membranes provide higher rejection rates, even for short chain PFAS such as PFBA and TFA. However, routine membrane cleaning is necessary to prevent fouling and maintain performance. Pre-treatment steps, such as nanofiltration, are often required to protect membranes and optimise efficiency, particularly when treating poor quality water ([Tang et al., 2006](#); [Flores et al., 2013](#); [ITRC, 2023](#)). In Germany, several water suppliers use RO to treat PFAS contaminated groundwater, typically as the final step in multi-stage water treatment processes. RO systems have demonstrated high effectiveness, even at PFOS concentrations as high as mg/L, with residential units achieving over 97% removal of various PFAS ([Riegel et al., 2020](#)). Although it has a high removal efficiency, RO presents challenges that limit its feasibility. These include high capital and operational costs, energy consumption, and routine maintenance requirements. Also, membrane fouling, high pressure operation, and the management of PFAS concentrated brine add to operational complexity further increasing costs. In turn, RO is more suited for high volume, low concentration targeted applications, such as drinking water treatment ([Held and Reinhard, 2020](#)).

5.2.4 Membrane Filtration

Membrane filtration techniques, including microfiltration, ultrafiltration, and nano filtration, separate contaminants from liquids primarily through size exclusion. Nano filtration membranes, with their smaller pore sizes (1-10m), are particularly effective for PFAS removal, achieving up to 99% efficiency in full scale groundwater treatment ([Franke et al., 2019a](#)). [Griffin et al., 2024](#) found tight NF to remove 92% of ultrashort-chain PFASs from

semiconductor wastewater. This process yields two streams: permeate (treated water) and concentrate (contaminant rich waste), which requires appropriate disposal.

Compared to reverse osmosis, nano filtration membranes generally consume less energy but are more prone to PFAS passage, particularly short chain compounds. Pretreatment is often needed to reduce fouling, especially at high flow rates, while periodic chemical cleaning helps maintain performance.

Combining nano filtration with other methods, can improve water recovery, improve treated water quality, and lower energy consumption. Advances in modified membranes featuring altered charges or functional groups show promise in improving PFAS separation efficiency ([Lee et al., 2022](#)). Although it is cost effective and scalable, nano filtration has limitations, particularly in managing concentrate waste streams and its difficulty to consistently reduce PFAS concentrations below some current drinking water standards ([Chaudhary et al.; 2023](#)). Membrane systems are typically designed independently of PFAS concentrations, which can impact operational efficiency. Also, competing contaminants may interfere with PFAS removal. A treatment train approach, where nano filtration or reverse osmosis serves as the primary removal step followed by a secondary technology for PFAS mineralisation, could offer a more complete remediation strategy ([Mastropietro et al., 2021](#)).

5.2.5 Colloidal Activated Carbon

Colloidal Activated Carbon (CAC) technologies, including polymer stabilised CAC solutions, are employed to improve *in situ* PFAS adsorption in groundwater. Injected via temporary wells, CAC forms a sorption zone that captures PFAS as contaminated groundwater flows through it. It also adsorbs contaminants back diffusing from low permeability zones, helping to reduce plume migration. Smaller grain size (micron-scale particles) also provides a higher surface area. Performance is influenced by site geochemistry, including levels of organic carbon, competing ions, and co contaminants. Injection typically follows a grid pattern in source zones or a transect across plumes ([ITRC, 2023](#)). This approach adsorbs both short and long chain PFAS for periods ranging from 0.3 to 6 years, even in the presence of low levels of organic co contaminants, but short-chain breakthrough often occurs much earlier ([McGregor, 2020](#); [Carey et al., 2022](#)). Commercial CAC solutions have undergone pilot and full scale implementation in several countries, demonstrating effective PFAS reductions ([Regenesis, 2022a](#); [Niarchos et al., 2023](#); [Regenesis, 2023](#); [Regenesis, 2022b](#)). Performance can be extended further by reapplication or reinforcement through additional CAC injections.

GAC, IX, and foam fractionation are pump-and-treat system which generate waste. In contrast, CAC generates no waste requiring no transport, disposal, or destruction ([Hall et al., 2024](#)). [Birnstingl and Wilson, 2024](#) provide a cost comparison of pump-and-treat and *in-situ* CAC for PFAS groundwater plume management. Pump and treat are likely better suited to long-term containment and plume management rather than complete cleanup of groundwater.

CAC offers long term, little maintenance, low impact remediation with minimal environmental disturbance. However, site specific conditions (e.g., hydrogeology) and aging effects may impact performance, and PFAS rebound may occur if adsorption sites become saturated or contaminant flow bypasses the treatment zone. Proper monitoring and design optimisation are essential to sustained effectiveness ([Liu et al., 2025](#)).

5.2.6 Foam Fractionation

The surfactant properties of PFAS cause them to accumulate at surface interfaces, particularly the air water interface. Foam fractionation leverages this characteristic to remove PFAS from water. In this process, gas bubbles are introduced into a PFAS contaminated liquid. The amphiphilic nature of PFAS means that the molecules adsorb to the gas liquid interface of the rising bubbles. These bubbles then accumulate at the top of the liquid column, forming a foam layer enriched with PFAS which can be removed. By relying solely on aeration, foam fractionation effectively separates PFAS based on surface activity without the need for chemical reagents or adsorbent media, making it a simple and potentially cost effective treatment method for complex matrices such as landfill leachate or AFFF ([Buckley et al., 2023](#); [We et al., 2024](#)). This method is particularly effective for removing high concentrations of long chain PFAS, achieving over 99% removal for compounds such as PFOS, PFHxS, and PFOA in groundwater. Notable applications include Surface Active Foam Fractionation (SAFF) technology, which achieved over 98.8% PFOS removal from landfill leachate in Sweden and reduced PFOS and PFHxS to below detection limits in AFFF impacted groundwater in Australia ([Burns et al., 2021](#); [Smith et al., 2022](#); [Stevenson, 2007](#); [EPOC Enviro, 2022](#)). Ozofractionation, which combines fractionation with ozone, is effective across a wide range of PFAS concentrations but is unable to consistently achieve the extremely low ng/L limits required by regulation. It is therefore more appropriate as part of a treatment train rather than a standalone solution ([Wanninayake et al., 2021](#)).

Foam fractionation provides quick volume reduction and does not require chemical additives, making it well suited for targeted applications. However, the effectiveness of foam fractionation declines with shorter chain PFAS and typically requires follow-up treatment. Foam fractionation may release PFAS into the air, posing potential worker exposure risks when air pollution controls are not in place ([Smith et al., 2023](#)). It performs best when PFAS levels exceed 0.5 µg/L. Flow rates are relatively low, limiting its suitability for large scale applications, and the management of PFAS rich foam remains a challenge. Research is ongoing into the use of co-foaming agents and the optimisation of bubble size and residence time to enhance performance.

A treatment train, where foam fractionation is combined with technologies that destroy PFAS, may improve outcomes. While it is a promising solution for long chain PFAS removal, further research and development are needed to enhance its effectiveness for short chain compounds, improve scalability, and compatibility.

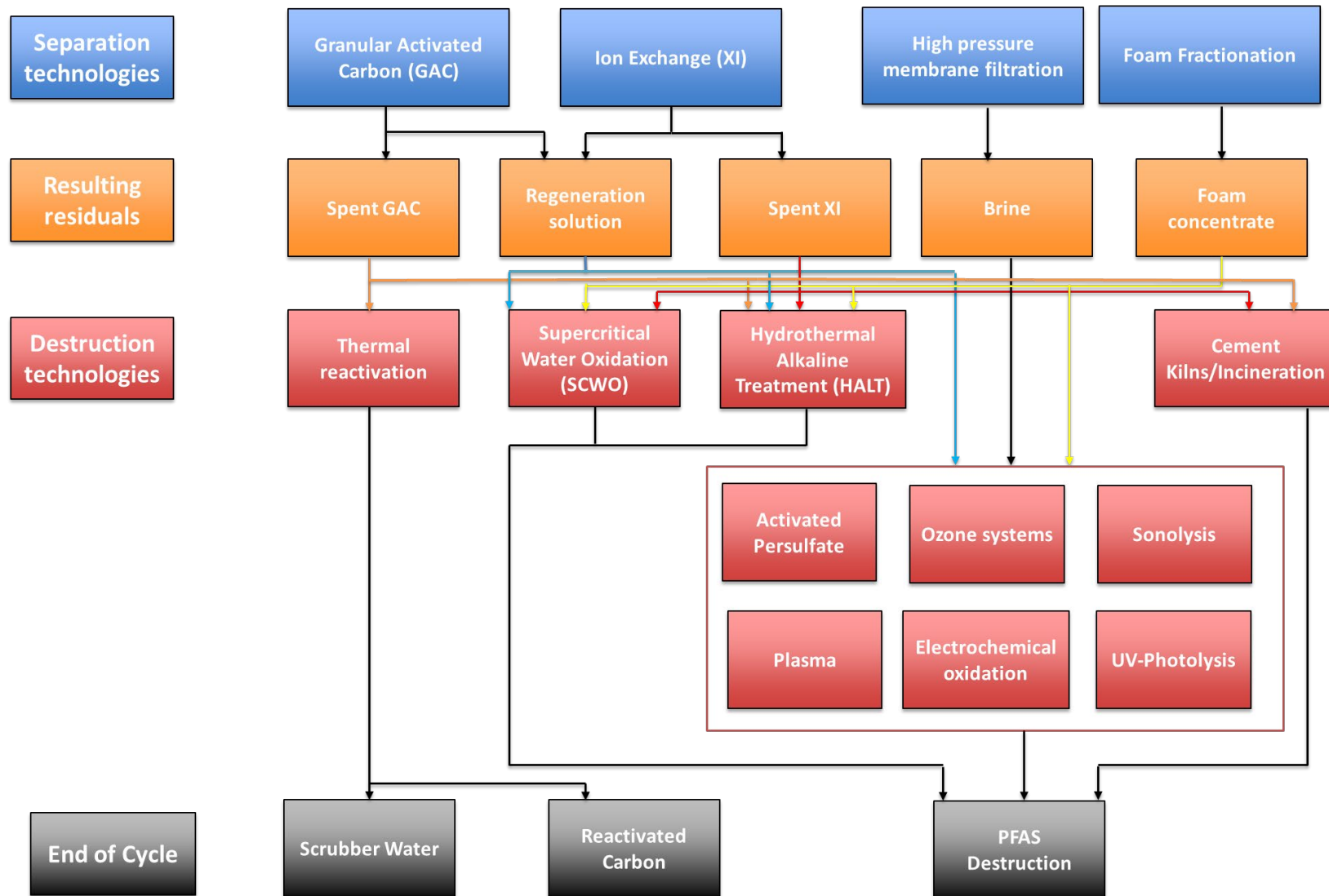


Figure 9. Management of PFAS by full scale separation technologies for water (modified and redrawn from [Environment analyst 2025](#))

Table 4. Overview of liquid remediation methods that have been successfully implemented at full scale under real world conditions for PFAS removal

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
<p>Granular activated carbon (GAC)</p> <p>Technology readiness level 9</p> <p>GAC thermal reactivation TRL 9</p>	<p>Highly effective for long-chain PFAS; less effective for short-chain PFAS (high surface area). PFASs generally removed more readily than PFCAs</p>	<p>Adsorption mainly via hydrophobic and electrostatic interactions</p>	<ul style="list-style-type: none"> - Proven technology, widely used - High efficiency for long-chain PFAS - Reactivable and reusable, low cost, simple and flexible - Minimal environmental impact when managed correctly - Feasible for large-scale applications (easily scalable) - Does not require technological devices - Can remove long chain PFAS to regulatory levels 	<ul style="list-style-type: none"> - Reduced efficiency/bed life for short-chain PFAS - Frequent replacement/reactivation required, increasing costs and impact. - Performance affected by competing substances, pH, temperature etc - PFAS-laden GAC disposal challenges i.e uncertainty on air emissions for reactivation - May need pre-treatment for complex matrices - Indication of saturation and exhaustion may be difficult - Thermal reactivation may affect adsorption properties and associated air emissions - Large footprint systems 	<ul style="list-style-type: none"> - Drinking water treatment - Industrial wastewater - Pre-treatment for IX resins - Adaptable to many existing treatment plants and can be applied for large-scale operations.
<p>Ion Exchange (IX) Resins</p>	<p>Highly effective for long-chain and moderately effective for</p>	<p>Adsorption and electrostatic attractions</p>	<ul style="list-style-type: none"> - High efficiency, good removal of PFOS (highly selective) - Longer lifespan than GAC 	<ul style="list-style-type: none"> - Rate of exchange influenced by many parameters i.e sensitive to dissolved organic carbon and co-contaminants - Requires pre-treatment for optimal 	<ul style="list-style-type: none"> - Drinking water treatment - AFFF contaminated groundwater - Industrial wastewater

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
<p>Technology readiness level 9 (without regeneration)</p> <p>7/8 (with regeneration)</p>	short-chain PFAS		<p>so potential lower long term operational cost</p> <ul style="list-style-type: none"> - Shorter empty bed contact time required - Regenerable, lowering long-term costs - Space efficient and simple operation and maintenance. - Easy integration to wastewater treatment processes. <p>Well established for full scale treatment and high waste to volume reduction</p>	<p>performance</p> <ul style="list-style-type: none"> - Disposal or regeneration creates complex waste stream (most resins are single use) - Less effective at removing uncharged, positively charged, and short-chain PFAS - PFAS-selective resins cannot be regenerated with conventional methods - Indication of saturation and exhaustion may be difficult - More expensive per unit than GAC - More sensitive to clogging from suspended solids than GAC - Uncertainty about completeness of PFAS destruction and associated air emissions during incineration 	
<p>Reverse Osmosis (RO)</p> <p>Technology readiness level 9</p>	Effective for long chain PFAS and less for short chain PFAS	Separation via semi-permeable membranes	<ul style="list-style-type: none"> - High removal efficiency across PFAS types - Removes additional contaminants i.e salts, pesticides etc and impurities - Established, proven technology - Produces high-quality permeate 	<ul style="list-style-type: none"> - High capital and operational costs - Energy-intensive due to pressure - Requires extensive maintenance especially for groundwater - Concentrate brine disposal adds complexity - Inefficient under poor water quality conditions - Can demineralise water and high-water 	<ul style="list-style-type: none"> - Proven effective landfill leachate - Drinking water purification - Industrial wastewater treatment - Pre-treatment for other technologies - Typically applied for large-scale drinking water and for

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			<ul style="list-style-type: none"> -Steady performance, no “breakthrough” like in GAC or IX. -Ability to treat large flow rates -Small footprint and applicable to most water matrices 	<ul style="list-style-type: none"> consumption - Requires extensive pretreatment to prevent membrane fouling. - Long-term decrease in PFAS rejection rate 	<ul style="list-style-type: none"> industrial and municipal wastewater.
<p>Membrane Filtration including nanofiltration (NF)</p> <p>Technology readiness level 9 for NF</p>	<p>High long chain PFAS removal for NF; lower for microfiltration and ultrafiltration (UF). Although UF is lower energy and can possibly be enhanced with modifications and used in treatment trains</p>	<p>Size exclusion via porous membranes</p>	<ul style="list-style-type: none"> - Effective for various PFAS (high removal efficiency) - NF requires less energy and pressure than RO - Modified membranes improve PFAS removal - Stable, reliable process - Compatible with other methods i.e. GAC - Removal of additional pollutants such as heavy metals 	<ul style="list-style-type: none"> - Lower efficiency for short-chain PFAS - High costs and maintenance needs - Membranes sensitive to fouling, limited volume reduction - Concentrate disposal require/waste treated before disposal - Requires periodic chemical cleaning i.e. pre and post treatment -Still high upfront costs - Removal efficiency can vary depending on membrane type and PFAS structure. 	<ul style="list-style-type: none"> - Groundwater treatment - Industrial wastewater -Pilot studies for drinking water - Combination with GAC or IX
<p>Colloidal Activated Carbon (CAC)</p>	<p>Highly effective for long-chain PFAS and</p>	<p><i>In situ</i> injection of polymer-stabilised CAC</p>	<ul style="list-style-type: none"> - Effective for both short and long-chain PFAS, >99.9% PFAS reduction over time -Long-term sequestration 	<ul style="list-style-type: none"> - Long-term performance can vary - Requires ongoing monitoring and maintenance as non-destructive - Potential rebound of PFAS 	<ul style="list-style-type: none"> - Groundwater treatment - Permeable reactive barriers

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
Technology readiness level 7	slightly less for short chain		<p>solution with sustained low PFAS levels</p> <ul style="list-style-type: none"> - Minimal site disturbance and easy deployment - Proven success in field-scale applications and simple - Environmentally friendly, no waste. - Can reduce concentrations to near detection limits - Lower energy than pump and treat 	<p>concentrations post-treatment</p> <ul style="list-style-type: none"> - Injection may require specialised equipment - Performance may vary based on groundwater conditions PFAS type, and site-specific hydrogeology - Competing organic materials/ions may reduce adsorption efficiency - Requires ongoing monitoring and possible re-injection to maintain performance. 	<ul style="list-style-type: none"> - Firefighting sites, airports, military airfields
Foam Fractionation Technology readiness level 7-8	High removal for long chain PFAS, less for shorter chain	Surfactant separation using gas bubbles. Air or gas is injected into the medium, creating a foam layer that concentrates PFAS.	<ul style="list-style-type: none"> - High removal efficiency for long-chain PFAS in bulk - Cost-effective - Simple operation, no major byproducts - Minimal additive use - High volume reduction - Insensitive to treated water matrix variations - Low energy and small concentrated waste stream - Can extend lifespan of downstream GAC/IX filters - Ozone fractionation provides 	<ul style="list-style-type: none"> - Less effective for short-chain PFAS (<6 perfluorinated carbons) without additives, As they are less prone to fractionation due to their higher solubility in water - Requires foam by-product management - Limited flow rates - Potential for secondary pollution if foam is mishandled (need for air controls) - High energy consumption in ozone fractionation - Operationally limited to concentrations 	<ul style="list-style-type: none"> - Groundwater treatment - Landfill leachate - AFFF-impacted groundwater - Pilot and field-scale applications

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			<p>additional oxidation of co-contaminants without competing with PFAS</p>	<p>>0.5 µg/L, hard to get contamination below regulatory limits. - Complex bubble dynamics not fully understood -High energy demand for ozofractionation so used as polishing method</p>	

5.3 PFAS Remediation Methods in Development

Innovative technologies are being developed to address PFAS contamination in both liquid and solid environments ([Tshangana et al., 2025](#); [Antonopoulou et al., 2024](#); [Geosyntec, 2024](#); [Verma et al., 2023](#); [US EPA, 2024e](#)). At present, destruction technologies are most effective for small volumes of concentrated PFAS waste in lab/pilot studies (spent sorbents). Scaling up to treat large volumes of contaminated water and soil remains a challenge. Current research is directed at improving throughput, energy efficiency, and cost-effectiveness to allow broader application. The following sections outline key emerging technologies, with a summary provided in Table 5.

5.3.1 Supercritical water oxidation (SCWO)

SCWO is an advanced technology that effectively destroys PFAS in aqueous matrices. Operating at temperatures above 374°C and pressures exceeding 22.1 MPa, SCWO leverages the unique properties of supercritical water, where organic solubility increases, and oxidation reactions accelerate. This enables rapid PFAS breakdown without the need for catalysts, achieving destruction efficiencies exceeding 99% for certain PFAS compounds ([Krause et al., 2021](#); [Austin et al., 2023](#); [Chiang et al., 2023](#)).

Batch SCWO reactors have demonstrated partial PFAS destruction, with a 70% reduction in PFOS at 500°C ([Pinkard et al., 2021](#)), while field-scale testing ([McDonough et al., 2022](#)) reported overall 63% defluorination when treating a concentrated waste stream containing 12 PFAAs at field scale. Pilot applications, have also shown success, reducing total measured PFAS concentrations by several orders of magnitude at 600°C and 3500 psi ([Scheitlin et al., 2023](#)). Recognising its potential as an alternative to incineration, the US EPA has identified SCWO as a promising treatment for PFAS-contaminated firefighting foams. It is also promising for treating IX brine/GAC fines. This approach is now also recognised in the Basel Convention General technical guidelines on environmentally sound waste management ([UNEP](#)).

While SCWO shows strong potential for PFAS destruction with some destruction efficiencies between 90 and 100%, several technical challenges remain. The high pressures and temperatures required can lead to equipment degradation and increase energy and maintenance costs ([Vadillo et al., 2013](#)). Additionally, volatile organofluorine compounds may form and corrosive byproducts such as hydrofluoric acid (HF) pose additional risks to worker safety, emissions control, and reactor integrity ([Zgonc et al., 2023](#)). These issues may be mitigated by using alkaline additives to neutralise acidity. Further research would be required to improve energy efficiency and lower costs to enable wider implementation.

5.3.2 Plasma Treatment

Plasma technology degrades PFAS in water by generating reactive species through high voltage electrical discharges, facilitating the breakdown of PFAS molecules ([Singh et al., 2019](#); [Palma et al., 2022](#)). Plasma technology exists in two forms: thermal plasma and nonthermal plasma, with the latter being more popular in water treatment due to its lower energy requirements. Bench scale studies using synthetic water, landfill leachate, and groundwater have reported certain PFAS removal efficiencies ranging from 36% to 99% ([Singh et al., 2019](#)), however, complete destruction was not achieved. Laboratory experiments have shown promising results: [Hayashi et al. \(2014\)](#) achieved approximately 98% decomposition of PFOA (initial concentration of 41.4 mg/L) using plasma within oxygen bubbles over three hours. [Stratton et al. \(2017\)](#) demonstrated a 90% reduction of PFOA within 30 minutes using electrical discharge plasma. Plasma technology may be considered cost effective and environmentally friendly in certain applications, producing relatively low greenhouse gas emissions ([Kumar et al., 2020](#)). Microbubble plasma reactors may boost reactions with lower energy use, and mobile units for demonstration are now used for on-site destruction of regenerants and firefighting foam concentrates. Factors like pH shifts, nitrate competition, high conductivity, or suspended solids can influence efficiency. Pretreatment may also be needed.

However, while it shows considerable promise, further research is needed to optimise large-scale applications and assess long-term environmental impacts. Though currently plasma technology holds strong potential as a scalable alternative to traditional incineration ([Ezeorba et al., 2024](#)).

5.3.3 Bioremediation

Bioremediation uses microorganisms, including bacteria and fungi to degrade or transform PFAS, with promising results ([Leung et al; 2022](#)). *Acidimicrobium sp.* strain A6 has shown up to 60% removal of PFOA and PFOS over 100 days ([Huang and Jaffé, 2019](#); [Ruiz-Urigüen et al., 2022](#)). Also, certain fungi can transform 6:2 FTOH into various degradation products ([Merino et al., 2016](#); [Tseng et., 2014](#)). Recent research by [Yu et al., \(2024\)](#) highlights that specific *Acetobacterium* species are capable of reductive defluorination of unsaturated PFAS, using specialised enzymes to cleave C-F bonds. However, only a limited number of microorganisms possess the necessary enzymatic pathways for effective PFAS degradation, and most of these studies focus on remediation of reactive polyfluorinated compounds. [Smorada et al., 2024](#) and [Bhattacharya et al., 2025](#) review the bioremediation of PFAS in more detail.

Interestingly, recent research has demonstrated that plant proteins derived from *Cannabis sativa L.* can break down up to 98% of PFOS and PFHxS within just one hour, significantly outperforming microbial degradation methods ([Vo et al., 2020](#)). While this enzymatic approach offers promising new possibilities for PFAS remediation, further investigation is required to evaluate its scalability and practical application in environmental contexts.

Although there is potential, a key challenge is the risk of transforming PFAS precursors into more mobile anionic PFAAs, which could complicate remediation efforts ([Ross et al., 2018](#), [Nathanail et al., 2024](#)). Laboratory studies indicate that microbial PFAS degradation is slow and often incomplete, making full scale bioremediation impractical at this stage. It is also very limited to precursor compounds. Complete and consistent mineralisation of PFOA/PFOS is not reliably shown. However, with ongoing advancements in microbial strain identification, genetic engineering, and enzyme characterisation, bioremediation could become a viable and sustainable PFAS treatment solution in the future ([Shahsavari et al., 2021](#)).

5.3.4 Electrochemical Oxidation (EO)

EO is a promising chemical treatment process that uses electricity to generate oxidative species at the electrode surface, breaking the C-F bonds in PFAS. The process occurs through either direct oxidation, where PFAS degrade upon adsorption onto the anode surface, or indirect oxidation, mediated by electroactive hydroxyl radicals (OH•). Boron doped diamond electrodes have shown high efficacy under ambient conditions, particularly in treating PFAS contaminated groundwater and landfill leachate, but are costly ([Fang et al., 2017](#)). Studies on both synthetic solutions and real world contaminated water have demonstrated >99% PFAS wastewater removal using EO ([Nzeribe et al., 2019](#); [Schaefer et al., 2020](#); [Veciana et al., 2022](#)). It has shown some efficacy in degrading short-chain PFAS, though these compounds remain more resistant to oxidation.

Advantages include operation at ambient conditions, ability to be deployed as a mobile unit, and no requirement for chemical oxidants as additives. Issues such as electrode corrosion, incomplete destruction of some PFAS, efficiency losses due to mineral build up on the anode, high cost of electrodes, potential volatilisation of contaminants and the formation of toxic byproducts, (e.g., hydrogen fluoride, bromate, perchlorate, and halomethanes) require careful management. EO has been integrated into treatment trains, combining groundwater and leachate abstraction, foam fractionation for PFAS concentration, and EO for degradation.

Although there are potential limitations, EO offers a lower energy (depending on electrode material and PFAS concentration) and temperature alternative to incineration for PFAS destruction and SCWO, holding promise in certain applications. The technology currently has an intermediate technology readiness level, and ongoing research and development would be required to improve its scalability, reduce operational costs, and better control by product formation ([Mirabediny et al., 2023](#); [Lin et al., 2018](#); [Niu et al., 2016](#)).

5.3.5 Ozone Based Systems

Ozone based systems generate oxidising species such as hydroxyl radicals and molecular ozone to degrade PFAS in water ([Lin et al., 2012](#)). While ozone alone is ineffective under neutral or acidic conditions, high pH levels notably improve its degradation potential. Combining ozonation with photolysis, activated persulfate and foam fractionation has

achieved over 95% removal efficiency in laboratory studies ([Dai et al., 2019](#); [Huang et al., 2016](#)). A bench scale study by [Eberle et al., 2017](#) using peroxone activated persulfate decreased PFAS by 99.9% using PFAS-contaminated site groundwater and spiked deionized water, though this reflects a combined oxidant system rather than ozone alone. A pilot ozonation system decreased PFAS from drinking water after 3 hours, though shorter-chain PFAS were generated during treatment ([Franke et al., 2019b](#)) Although effective as a possibly a polishing method, ozonation has not yet demonstrated complete destruction in field applications ([Kerfoot, 2014](#)). Further research and development are needed to improve scalability and operational reliability ([Thomas et al., 2020](#)).

5.3.6 Photolysis and Photocatalytic Degradation

Photolysis relies solely on the direct photochemical cleavage of C-F bonds. While Photocatalytic degradation of PFAS occurs through either photo-oxidation or photo-reduction, driven by natural (e.g., solar) or artificial (UV) radiation. These processes may occur with or without the use of photochemical catalysts, including chemical oxidants (e.g., persulfate, iron, Fenton's reagent, sulphite) or catalytic anodes (e.g., TiO₂, TiO₂/O₃, SiC/graphene) ([Wang et al., 2017](#); [ITRC 2023](#); [Gomez-Ruiz et al., 2018](#)). In photo-oxidation, highly reactive oxidative species are generated that can degrade PFAS ([Cao et al., 2024](#); [Chen et al., 2007](#); [Hori et al., 2004](#)). In photo-reduction, C–F bonds are directly cleaved by reductive species such as solvated electrons. This pathway is generally considered more favourable for PFAS defluorination ([Geosyntec, 2024](#)).

Bench and pilot scale studies have shown promising results, with some systems reducing PFAS concentrations in drinking water to below detection limits within 60 minutes ([Qanbarzadeh et al., 2021](#)). Key factors influencing performance of photocatalytic degradation include light wavelength, catalyst concentration, initial PFAS concentration, pH, reaction atmosphere, temperature, water chemistry, and reactor design. Natural photolysis can degrade long-chain PFAS to short-chain forms, but the resulting short-chain PFAS are resistant to further breakdown ([Taniyasu et al., 2013](#)). Photolysis alone cannot break most PFAS C–F bonds except under extreme UV wavelengths (<200 nm). [Verma et al., 2024](#) and [Tshangana et al., 2025](#) provide more detail on the photodegradation and photocatalysis of PFAS.

Most research is still experimental. While promising, photocatalysis is less effective than other destructive methods. It can produce toxic byproducts and is affected by co-contaminants and challenges in recovering TiO₂. However, ongoing technological progress offers potential for broader application ([Meegoda et al., 2022](#); [Liu et al., 2017](#)).

5.3.7 Hydrogen Peroxide and Activated Persulfate

Heat-activated persulfate (S₂O₈²⁻) and hydrogen peroxide (H₂O₂) have been shown to oxidise certain PFAS ([Mitchell et al., 2014](#); [Bruton and Sedlak, 2017](#); [Teel et al., 2007](#); [Watts et al., 2005](#); [Park et al., 2016](#)). Bench scale catalysed hydrogen peroxide demonstrated up to 89% degradation of PFOA within 150 minutes ([Mitchell et al., 2014](#)). It

is typically paired with UV light. Even with promising degradation rates, challenges may remain. Further optimisation via a treatment train is likely required to improve scalability and ensure efficient large-scale application ([ITRC 2023](#)).

5.3.8 Zero Valent Iron

Zero valent iron (ZVI) is a cheap groundwater treatment method and can be coupled with UV light ([Xia and Liu, 2020](#)). Nanoscale ZVI offers increased reactivity and a larger surface area, making it well suited for *in situ* applications. PFAS removal primarily occurs through adsorption, reduction, and desorption ([Arvaniti et al., 2015](#)). PFOS removal efficiencies have been demonstrated through adsorption and reduction, with Mg aminoclay coated Nanoscale ZVI yielding particularly promising results. ZVI has been tested in various conditions. While Nanoscale ZVI is semi effective and relatively fast for PFOS removal, its performance with other PFAS such as PFOA varies ([Lawal and Choi, 2018](#)). Overall, ZVI offers a solution for PFOS removal ([Fang et al., 2024](#)), though its efficacy depends on the specific PFAS targeted and site conditions, requiring further research ([Hori et al., 2006](#); [Zenobio et al., 2020](#)).

5.3.9 Hydrothermal alkaline treatment

Hydrothermal alkaline treatment employs hydrothermal conditions (high temperature (~350°C, high pressure, and high pH conditions) in water to initiate fast defluorination reactions. The process promotes chain shortening and decarboxylation ([Wu et al., 2019](#)). Continuous flow systems have demonstrated over >99% PFAS destruction after 10 minutes of treatment ([Pinkard et al., 2023](#)). [Hao et al., 2021](#) reported that 109 PFAS identified in two AFFF formulations were largely degraded to below detection limits within 15 minutes. Although generally long residence times (> 30 minutes) have been needed for PFAS degradation. Recent studies indicate that HALT-treated GAC can be reused with no significant loss in adsorption efficiency, supporting circular economy approaches ([Soker et al., 2025](#)). While HALT shows promise, further pilot and field scale studies are necessary to validate its scalability and cost effectiveness ([Hao et al., 2022, 23](#); [ITRC 2023](#)).

5.3.10 High Energy Electron Beam (eBeam)

eBeam technology is a high-efficiency, non-thermal, chemical-free, flow-through process that that utilises ionising radiation from electron accelerators in liquid or solid matrices. Although, a limited number of studies have utilised e-beam to study the degradation of PFAS in aqueous matrices ([Londhe et al., 2024](#)). Commonly used in applications such as food pasteurisation and medical sterilisation ([Pillai and Shayanfar, 2017](#)), eBeam has demonstrated promising PFAS defluorination in water, with high removal efficiencies observed in bench-scale studies ([Kim et al., 2019](#); [Ma et al., 2017](#); [L. Wang et al., 2016](#)). However, broader adoption faces challenges, including energy demands, operational costs, and the large size of equipment required ([Londhe et al., 2021](#); [Praveen et al., 2013](#); [Jiang et al., 2022](#)).

5.3.11 Precipitation/coagulation/flocculation

These partially developed methods are frequently used for wastewater pretreatment, removing various particles and dissolved constituents ([ITRC 2023](#)). Coagulation is a chemical process where coagulants are added to neutralise the charge on particles, allowing them to form larger masses. These masses become heavy enough to settle out of the water. Flocculation follows as a physical process, where gentle stirring encourages the neutralised particles to clump together into larger flocs that can then be removed through filtration ([UKWIR, 2025](#)). Coagulation and flocculation have been used in the Netherlands and Germany for PFAS-contaminated groundwater, achieving >90% removal of long-chain PFAS but lower efficiency for short-chain compounds; the resulting PFAS-rich sludge requires further destruction ([Goelen, Lescrauwaet, Vander Aa and Janssens, 2023](#)).

Electrocoagulation is a non-destructive method that can be used for drinking water and wastewater treatment. It uses metal hydroxide flocs to adsorb contaminants. The electric current triggers electrolytic oxidation of a sacrificing anode and production of hydroxide ion at the cathode ([Mu et al., 2021](#)). Metal hydroxide flocs can remove contaminants through adsorption and are then removed from solution requiring appropriate disposal ([Hussain et al., 2025](#)). Electrocoagulation has shown superior removal efficiency than conventional coagulation ([Baudequin et al., 2011](#); [Lin et al., 2015](#); [Y. Wang et al., 2016](#); [Xiao et al., 2013](#); [Yang et al., 2016](#)). [Hubert et al. \(2024\)](#) reported high removal rates for long chain PFAS using PerfluorAd and cationic flocculants. Electrocoagulation is promising for PFAS. However, pilot and full-scale applications are largely untested.

PFAS removal in these systems is influenced by factors such as anode type, current density, stirring speed, electrolytes, organic matter, electrolysis time, and anion effects ([Birk, 2017](#)). Overall, electrocoagulation appears more efficient and feasible, with potentially lower environmental impacts than conventional methods like precipitation, coagulation, and flocculation.

5.3.12 Ball Milling

Ball milling degrades PFAS by mechanically breaking C-F bonds through high-speed collisions between metal balls and additives. The process is often improved with co reagents like potassium hydroxide or sand, though recent advancements using boron nitride have achieved good PFAS degradation within hours under ambient conditions. It is considered a sustainable technique method when compared alternatives. ([Yang et al., 2023](#)). Laboratory and pilot-scale studies have demonstrated PFOS and PFOA reductions of 42 to >90%, with some cases achieving near-complete fluoride recovery. 100% removal efficiency of 6:2 fluorotelomer sulfonate (6:2 FTS) has been reported when KOH was co-milled with PFOA, PFOS, and 6:2 FTS in a planetary ball mill ([Yu et al., 2025](#))

Ball milling is particularly suited for small volume source areas or biosolids. However, it can alter soil structure, necessitating post treatment steps such as drying, screening, and pH adjustment. While the technique has been successfully applied to non PFAS contaminants like dioxins, its large-scale implementation for PFAS faces logistical

challenges, including soil handling, reagent consumption, and processing rates. Mechanochemical degradation, may also generate gaseous emissions because of incomplete breakdown of PFAS compounds. Even with these limitations, ball milling remains a promising PFAS destruction method and alternative to incinerating solids, particularly for targeted remediation efforts where conventional treatment options are impractical. More research is needed to assess its scalability and field applicability ([Battye et al., 2022](#); [Gobindlal et al., 2023a](#); [Gobindlal et al., 2023b](#); [Yang et al., 2025](#)).

5.3.13 Sonolysis

Sonochemical degradation uses high frequency ultrasound waves to create vapor bubbles that collapse under extreme temperatures (~5000K), generating hydroxyl radicals and promoting the pyrolysis of PFAS, primarily at the bubble air water interface. This process achieves effective defluorination of compounds like PFOS and PFOA without requiring harsh chemicals or extreme conditions ([Meegoda et al., 2022](#); [Saawarn et al., 2022](#)). Additives such as persulfate, periodate, or salt ions can increase degradation efficiency. Combining sonolysis with UV or photocatalytic degradation can further improve outcomes. Key operational parameters include ultrasonic power density, frequency, temperature, and atmospheric conditions. While sonolysis shows promise for PFAS mineralisation, it has niche application with further optimisation of energy efficiency, scalability, and field applications required ([Mayakaduwage et al., 2022](#); [Sidnell et al., 2022](#); [Cao et al., 2020](#); [Held and Reinhard, 2020](#)).

5.3.14 Smouldering Combustion

Smouldering is a flameless thermal treatment that generates heat through the interaction of an oxidant (e.g., air) with a condensed fuel source, such as contaminated soil or spent GAC. The process can be improved by blending the fuel with inert media, like sand, to improve heat transfer. During smouldering, the fuel undergoes thermal decomposition, resulting in the oxidation of organic contaminants, leaving behind treated material. Originally applied for treating sewage biosolids and hydrocarbon contaminated soils, smouldering is now being investigated for PFAS remediation ([Fournie et al., 2023](#)). [Duchesne et al. \(2020\)](#) evaluated smouldering combustion for PFAS contaminated soil and GAC, achieving temperatures of up to 900°C. The study reported 44% PFAS destruction in GAC and 16% in soil, with minimal emissions (<1%) effectively captured by GAC, highlighting smouldering's potential as a potential PFAS treatment method ([Winchell et al., 2021](#); [Major., 2019](#)). Compared to HTI and other thermal technologies, smouldering requires less energy and is more cost effective, making it an attractive lower cost alternative. Although there are promising results from laboratory and pilot scale studies, more full-scale applications across various matrices have yet to be demonstrated.

5.3.15 Phytoremediation

Phytoremediation employs plants and their associated microorganisms, enzymes, and water uptake to treat PFAS contaminated soil and groundwater through mechanisms such as phytoextraction and phytosequestration. While still in the experimental phase, with limited laboratory and pilot scale results, it may be suitable for shallow sites with low PFAS concentrations, minimal risk, and favourable conditions for plant growth. However, treatment durations may extend over decades. Plant selection is critical for effective PFAS uptake. Fast growing species like river birch, black willow, and red fescue show potential, though their removal rates are slow ([Concawe et al., 2024](#)). Wetland species appear more promising, with pilot scale studies reporting good removal efficiencies of for PFOA and PFOS after 15 days ([Chen et al., 2012](#)). Shorter chain PFAS are more readily moved within plant tissues, while long chain PFAS tend to accumulate in the roots due to stronger soil sorption ([D. Huang et al., 2021](#)). Managing contaminated plant biomass is necessary to prevent PFAS reintroduction into the environment or food chain. Further disposal, potentially through HTI, may be necessary. Identifying nonaquatic plant species capable of extracting long-chain PFAS could broaden the applicability of this approach. Even with current limitations, phytoremediation holds promise as a sustainable PFAS treatment method, particularly with further advancements in plant selection and biomass management ([Kavusi et al., 2023](#); [Concawe et al., 2024](#); [Chen et al., 2025](#); [Mayakaduwage et al., 2022](#)).

5.3.16 Thermal Desorption

Thermal Desorption involves heating PFAS contaminated soil either *ex situ* or *in situ* to volatilise PFAS, which are then captured using filtration systems and incinerated or landfilled. Operating at temperatures between 350°C and 450°C, thermal desorption consumes less energy than incineration but has a higher carbon footprint compared to methods like soil washing or stabilisation, particularly when factoring in energy intensive processes such as GAC reactivation ([Crownover et al., 2019](#)).

Although thermal desorption shows potential for PFAS removal, it has not yet been fully implemented at scale, with high costs presenting a barrier relative to other remediation options ([Verma et al., 2023](#)). Thermal Desorption may be advantageous in scenarios where soil washing or stabilisation is impractical, such as for cohesive soils or where disposal options for stabilised soils are limited. However, further research is needed to improve cost-efficiency, mitigate by potential short chain PFAS formation, optimise filtration systems, and address gaps related to air emissions and the fate of volatilised PFAS. Although, [Sörengård et al., 2020](#) reported at 450°C, over 90% of certain PFAS were removed from the fortified soils.

5.3.17 Pyrolysis and Gasification

Pyrolysis and gasification are emerging thermal treatment technologies that offer promising alternatives to incineration for managing PFAS-contaminated waste. Pyrolysis takes place in an oxygen-free environment at moderate temperatures, whereas gasification operates under limited oxygen conditions with partial combustion at higher temperatures. Compared to conventional incineration, these methods reduce airflow requirements, lower emissions, and decrease pollution control costs. Pyrolysis, in particular, functions at lower temperatures and breaks down organic materials into biochar and syngas within a reducing atmosphere. This process not only reduces energy consumption but also limits CO₂ emissions by converting a significant proportion of carbon into stable biochar ([Huber et al., 2009](#); [Kundu et al., 2021](#)).

Biochar improves soil quality, while syngas can be utilised as an on-site energy source. Gasification presents a viable alternative to sewage biosolids incineration, with potential applications in cement production and aggregate materials. [Berg et al., 2022](#) identified supercritical water oxidation (SCWO) for PFAS-containing AFFF and pyrolysis for biosolids as the most promising methods for achieving potential PFAS mineralisation ([Bamdad et al., 2022](#)). Although some studies suggest the possibility of complete PFAS defluorination, current research indicates that pyrolysis primarily breaks down PFAS into short chain fluorinated organic compounds within the syngas rather than fully mineralising them. As a result, the overall destruction efficiency of pyrolysis remains unverified ([J. Zhang et al., 2023](#); [Longendyke et al. 2022](#)).

Successive combustion of syngas at 1,000°C is required for complete PFAS mineralisation. However, incomplete characterisation of PICs raises emission uncertainties. A pilot study by [Thoma et al., \(2022\)](#) demonstrated that pyrolysis reduced PFAS concentrations in biosolids to below detection limits, but further validation is needed to assess by-products and confirm mineralisation efficiency. Despite, their potential, commercial adoption of pyrolysis and gasification remains limited due to high capital costs, a lack of operational facilities, and insufficient long-term performance data. Further research is needed to optimise process efficiency and ensure safe management of by-products. Nevertheless, these technologies present promising alternatives to incineration for treating PFAS in wastewater treatment plant solid residuals and PFAS-impacted biosolids ([US EPA 2021b](#)).

Table 5. Outlines technologies that are being developed to address PFAS contamination in both liquid and solid environments

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
Supercritical Water Oxidation (SCWO) Technology readiness level 5-6	High	Uses supercritical water conditions (high temperature and pressure) for thermal oxidation of PFAS.	<ul style="list-style-type: none"> -Rapid treatment; minimal environmental impact and non-selective - No catalysts or harmful residues or additives -Scalable and versatile and may recover energy from reactions -Degradation of PFAS at low concentrations 	<ul style="list-style-type: none"> -High operational temperatures and pressures - Costly and complex - Less economic for large volumes, need for supplemental fuel -Precipitation of salts -Build-up of corrosive species during oxidation 	<ul style="list-style-type: none"> - Industrial waste - Biosolids - Groundwater - Landfill leachate - AFFF and aqueous matrices; proven at bench and field scales
Plasma Treatment Technology readiness level 6	Moderate to high (more effective for long chain)	Electric discharge generates reactive species (e.g., hydroxyl radicals, atomic oxygen) to degrade PFAS	<ul style="list-style-type: none"> - Short treatment time - Minimal chemical input - Environmentally friendly/low energy - Can degrade other pollutants and precursors - Applicable to various matrices -Highly effective for long chain PFAS -Less prone to scaling 	<ul style="list-style-type: none"> - Requires further optimisation for large-scale use, high energy - High acidity due to pH reduction, potential byproducts - Mechanism not fully understood Long-term impacts need evaluation, risk of incomplete breakdown Longer time for short chain treatment 	<ul style="list-style-type: none"> - Landfill leachate - Groundwater - Industrial wastewater; effective at bench and pilot scales

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			and electrode fouling -Limited matrix influence	- The addition of chemicals is not necessary; however, non-specific reactions may lead to extended treatment times -Initial investment	
Biodegradation Technology readiness level 3	Moderate	Microorganisms (e.g., bacteria, fungi) and enzymes degrade or transform PFAS over time	- Low cost - Reduced energy demand Minimal environmental disturbance -Could scale well	- Slow and incomplete degradation for long-chain PFAS - Still under development as inconsistent results -small scale application -Incomplete understanding of degradation mechanisms, field applicability, and microbial adaptation	- PFOA and PFOS - PFAS precursors - Research ongoing to enhance efficacy
Electrochemical Oxidation (EO) Technology readiness level 3-5	High	Direct oxidation at the anode or via hydroxyl radicals in an electrochemical cell (strong electrical currents break C-F bond).	- Operates under ambient conditions - No additional chemicals required - Effective for direct and indirect oxidation. -Simple compared other processes, effective short chain PFAS -Long lifespan, energy efficient, low	- High energy consumption but can be cost effective - Complex scalability - Toxic by-products - Partial formation of short-chain PFAS -Boron-doped diamond, besides being challenging to produce is costly Slow in lab conditions. -Competing constituents interfere	- Groundwater - Landfill leachate - Still bottoms - Industrial effluents; promising lab results but real-world challenges exist, suitable for small to medium

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			environmental impact -Short operation time	with PFAS removal -Electrode fouling	sized applications
Ozone-Based Systems Technology readiness level 2-4	Moderate to high	Ozone and hydroxyl radicals degrade PFAS, especially at high pH levels	- Effective at high pH - Can be combined with other technologies for improved performance	- Limited efficiency at neutral or acidic pH - Potential generation of short-chain PFAS - Limited mechanistic data	- Drinking water - Groundwater - PFAS-contaminated soils; demonstrated bench success, ongoing field trials
Photolysis/Photocatalysis Photocatalytic Degradation Technology readiness level 5 Photolysis Degradation Technology readiness level 4	Moderate to High	UV or solar radiation generates radicals (e.g., hydroxyl radicals) that break down PFAS, aided by catalysts	- Effective with UV/solar radiation so potential to operate under standard conditions - Sustainable - Catalysts (e.g., TiO ₂) enhance degradation rates and can be reused - Low energy -Used as first step in PFAS treatment since has lower efficiency levels and incorporated	- Inefficient for sulfonic groups - Short-chain PFAS resist degradation - Technical issues (performance varies with light source and environmental conditions) -Toxic intermediate products, affected by co-contaminants -Long treatment times -Low degradation efficiency -Scalability challenges	- Drinking water - Groundwater - PFAS-contaminated soils; undergoing pilot-scale testing - Used as a first step in PFAS treatment

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			into other technologies easily		
Catalysed Hydrogen Peroxide (CHP) Technology readiness level 5-6	Moderate to High	Hydrogen peroxide decomposes to hydroxyl radicals, facilitating PFAS degradation	<ul style="list-style-type: none"> - Strong oxidant system - Adaptable to various catalysts 	<ul style="list-style-type: none"> - Limited data for large-scale use 	<ul style="list-style-type: none"> - Groundwater - Wastewater; requires additional field trials for broader application
Zero-Valent Iron (ZVI) Technology readiness level 5	Moderate	PFAS adsorb onto ZVI surface where reduction and transformation occur, often enhanced by UV	<ul style="list-style-type: none"> - Cost-effective - Highly reactive nanoscale ZVI suitable for <i>in situ</i> applications - Good removal for PFOS - Reacts relatively quick 	<ul style="list-style-type: none"> - Limited efficiency for some PFAS - Reactivity depends on surface conditions - Adsorption-based with limited destruction 	<ul style="list-style-type: none"> - Groundwater
Hydrothermal Alkaline Treatment (HALT) Technology readiness level 4-6	High	Under high-temperature, high-pressure, and alkaline conditions, water behaves more like a non-polar solvent, creating a highly reactive environment. This environment can catalyse various reactions and has	<ul style="list-style-type: none"> - Rapid destruction of PFAS - Effective for high-concentration, low-volume waste - Applicable to diverse PFAS 	<ul style="list-style-type: none"> - High chemical and energy requirements - Pilot and field-scale validation needed - Less suitable for large-volume, low-concentration waste - Corrosive environment, infrastructure durability 	<ul style="list-style-type: none"> - High-concentration, low-volume PFAS waste - AFFF concentrates - Proven at bench-scale

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
		been shown to degrade PFAS within minutes.		concerns - Chemical addition	
High-Energy Electron Beam (eBeam) Technology readiness level 4	Moderate to High	eBeam degrades PFAS using high-energy electrons that generate reactive radicals through advanced oxidation and reduction	- High efficiency for PFOS and PFOA - Non-thermal process - No chemical additives required -Used on a technical scale in other areas	- High energy consumption - Large equipment size - Complex and costly system	- Groundwater - Wastewater - Landfill leachate - Applicable for heavy hydrocarbon-contaminated soils and sewage biosolids disinfection
Coagulation/Precipitation/Flocculation Technology readiness level 6 for Coagulation/Flocculation Technology readiness level 5 for Electrocoagulation	Moderate, good removal of high concentrations of long-chain PFAS Electrocoagulation shows most potential	Formation of chemical complexes or adsorbing PFAS onto flocs, which are then separated from water	- High efficiency, especially with electrocoagulation - Robust and reliable - Easy to adjust parameters - Compact systems, no need for external coagulants. Can be combined with activated carbon	- Less efficient for short-chain PFAS although optimisation through dosing is possible - High initial costs for electrocoagulation systems - Post-treatment often still required i.e biosolids disposal challenges - Continuous electricity demand	- Industrial wastewater - Groundwater remediation - Municipal water treatment

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			-High waste volume reduction of the PFAS-containing fraction	-Effectiveness may be affected by water chemistry	
Ball Milling Technology readiness level 3-5	Moderate to High	High-speed collisions of metal balls mechanically break C-F bonds in PFAS	<ul style="list-style-type: none"> - Cost-effective - Efficient for solid matrices - Demonstrated high PFAS degradation in soils - Possibly meet sustainable goals 	<ul style="list-style-type: none"> - Limited data on large scale applications - Operating problems (noise, temperature, breakage of balls) needs further research and optimisation - Unclear degradation mechanism 	<ul style="list-style-type: none"> - Contaminated soils - Industrial wastes - Potential for future mechanical PFAS degradation technologies
Sonolysis Technology readiness level 4-5	Moderate to High	Uses high frequency sounds waves to generate and implode vapor bubbles in water, creating high temperatures (around 4700°C) that drive degradation via radical reactions and pyrolysis	<ul style="list-style-type: none"> - Highly effective for PFOS and PFOA - No need for chemical additives or extreme conditions - Low environmental impact - Effective for highly concentrated PFAS -No pretreatment needed, simple operation and compatible with 	<ul style="list-style-type: none"> - Limited to lab-scale studies, optimisation of ultrasonic and geometric parameters is required for scaling up the technology - High energy consumption -Requires further research for scalability and cost reduction - Mechanism not fully understood - Can be inhibited by contaminants -The shorter the PFAS chain, the 	<ul style="list-style-type: none"> - Soil and landfill leachate PFAS treatment - Ongoing research for broader applications

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
			<ul style="list-style-type: none"> other technologies -Mineralisation possible 	<ul style="list-style-type: none"> longer the treatment time - Affected by external influences 	
<p>Smouldering combustion</p> <p>Technology readiness level 3-4</p>	Moderate to high	Flameless thermal treatment sustained by heat from the oxidation of a condensed solid or liquid matrix (e.g., GAC) as fuel. The process can be enhanced by mixing fuel with inert media like sand for thermal transfer	<ul style="list-style-type: none"> - Possibly cost-effective with low external energy input after ignition - Effective for solid media (e.g., spent GAC, contaminated soil) - Non-detect PFAS levels in treated sand/ash 	<ul style="list-style-type: none"> - Lower PFAS destruction efficiency compared to other thermal technologies - May require high GAC concentrations - Possible release of by-products or PICs - Possible high engineering costs i.e vapor phase capture 	<ul style="list-style-type: none"> - Treatment of PFAS-contaminated soil - Spent GAC - Potential integration into broader treatment strategies
<p>Phytoremediation</p> <p>Technology readiness level 3</p>	Moderate	Uses plants and associated microorganisms to remediate PFAS-contaminated soil and groundwater through phytoextraction and phytosequestration.	<ul style="list-style-type: none"> - Sustainable, passive and low-cost - Minimal environmental impact - Suitable for long-term, passive remediation. 	<ul style="list-style-type: none"> - Still in the experimental stage - Slow removal rates - Long treatment durations required - Biomass disposal challenges. -Not viable for serious contamination scenarios. 	<ul style="list-style-type: none"> - Shallow, low-risk PFAS-contaminated areas - Constructed wetlands - Sites with suitable plant growth
<p>Pyrolysis</p>	Moderate to High (Potential for high)	Decomposes materials in an oxygen-free environment at moderate temperatures,	<ul style="list-style-type: none"> - Reduces waste volume by >90% - Generates biochar (soil 	<ul style="list-style-type: none"> - Limited commercial adoption and high capital costs compared to land application 	<ul style="list-style-type: none"> - Treatment of PFAS-contaminated

Remediation technique and TRL	PFAS removal efficiency	Mechanism	Advantages	Disadvantages	Specific and Potential Applications
Technology readiness level 5-6	destruction efficiency)	producing biochar and syngas	amendment) and syngas (energy source) - Requires less airflow than incineration, reducing emissions	- Potential formation of PICs - Further validation needed	biosolids - Potential use in WWTP biosolids management - Industrial waste treatment
Thermal Desorption Technology readiness level 5-6	Moderate to High (depends on temperature and PFAS chain length)	Heating PFAS-contaminated soil to volatilise PFAS, followed by air-phase capture and incineration	- Effective for a broad range of PFAS - Adaptable for both <i>in situ</i> and <i>ex situ</i> applications Removes PFAS from solids	- High energy costs - Potential formation of transformation products - Requires robust gas capture and treatment systems -Potential uneven heating	- Industrial and landfill sites - Soil preparation for further remediation

5.4 Sorption Methods in Development

Various sorbent materials, such as biochar, hydrogels, polymer coated sand, zeolites, and clay minerals, are being developed for PFAS remediation ([Geosyntec, 2024](#)). These materials are used in both *in situ* and *ex situ* treatment systems to address contamination across different matrices. However, short chain PFAS are particularly challenging to remove with sorption-based methods due to their higher water solubility and lower hydrophobicity ([ITRC, 2023](#)). It is also important to highlight that sorption is not a destructive treatment; unless the concentrated sorbent is removed and treated, it serves only as a temporary solution. [Goelen, Lescauwae, Vander Aa and Janssens, 2023](#) provide a more detailed explanation of these sorption methods.

Biochar, can be produced through biomass pyrolysis, has demonstrated potential for PFAS removal, with bench scale studies reporting performance comparable to GAC. However, pilot scale trials consistently show that GAC outperforms biochar due to the variability in biochar's properties ([Ahmad et al., 2014](#); [Guo et al., 2017](#)). Further research is necessary to optimise biochar for large-scale applications and confirm its long term efficacy ([Inyang and Dickenson, 2017](#); [Xiao et al., 2017](#)).

Fluorogels and hydrogels effectively remove PFAS through fluorophilic sorption and targeted ion exchange. These materials achieve over 90% removal for long chain PFAS, though slightly lower efficiencies (~60%) are observed for short chain variants such as PFBA. Their high selectivity and regenerability make them promising for industrial and environmental applications ([Ateia et al., 2019](#); [Kumarasamy et al., 2020](#)).

Polymer coated sand and cyclodextrin polymers offer efficient PFAS sorption. Coated sand performs comparably to GAC and demonstrates high regenerability. Cyclodextrin based polymers, functionalised for improved electrostatic interactions, facilitate effective PFAS removal and have shown promise in pilot scale applications. Both materials have potential to address a broader range of organic pollutants alongside PFAS ([Bhattarai, 2011](#); [Yang et al., 2020](#); [Badruddoza et al., 2017](#)). Continued research and development are needed to advance these technologies towards full scale deployment.

Zeolites and clay minerals are well established sorbents widely used for pollutant removal due to their high surface area, porous structure, ion exchange capacity, and cost effectiveness ([Delkash et al., 2015](#); [Han et al., 2019](#); [Tao et al., 2006](#)). Surface modified clays exhibit higher PFAS adsorption, enabling more efficient and targeted removal ([Zhou et al., 2010](#)). Both materials are suitable for *ex situ* and *in situ* PFAS treatment, with tailored clay minerals showing particular promise ([Li et al., 2023](#); [Mancinelli et al., 2022](#)). However, the *in situ* application of zeolites and clays is less studied, and further research is required to validate their real world effectiveness ([Ochoa-Herrera and Sierra-Alvarez, 2008](#); [Punyapalukul et al., 2013](#)).

6. Treatment Trains for Remediation

Differences in cost, efficiency, treatment time, resistance to co-contaminants, scalability, by-product formation, and environmental impact mean that each technology has clear trade-offs.

Treatment trains, integrated systems combining multiple remediation processes, have gained increasing attention in both academic and professional communities as a promising approach. These systems incorporate sequestration and/or destruction technologies to improve PFAS removal while reducing treatment costs, energy demands, and long-term environmental liabilities ([Wanninayake et al., 2021](#); [Babu et al., 2016](#); [Geosyntec, 2024](#); [Lu et al., 2020](#); [Zgonc et al. 2023](#)) Therefore, potentially overcoming the limits of single remediation technologies.

Treatment trains **may** offer several key benefits, including:

- **Optimising resource use and reducing system footprint** – Combining technologies may reduce system footprints and space requirements, improving efficiency.
- **Lowering energy demands and operational costs** – Planned integration may enhance overall performance, reduce expenses and improve resource use.
- **Reducing waste disposal** – Certain treatment configurations may integrate on site destruction technologies, which can reduce or eliminate PFAS waste accumulation and simplifies logistics.

For example, due to the diverse properties of PFAS, no single sequestration method effectively removes all variants. Granular activated carbon (GAC) efficiently adsorbs long chain PFAS but has limited effectiveness for short chain compounds, whereas Ion exchange resins (IX) are slightly more effective for short chains. Hybrid sorption systems combining GAC and IX could improve the removal of short-chain PFAS while also addressing competition from natural organic matter and long-chain PFAS ([Ateia et al., 2019b](#)).

To prevent the re-release of captured PFAS, sequestration technologies may be paired with destructive processes. Traditionally, spent PFAS laden media (e.g., GAC) has been transported off site for disposal via landfilling or via thermal treatment. However, emerging destruction methods such as plasma treatment, hydrothermal alkaline treatment, ball milling, electrochemical oxidation and supercritical water oxidation (SCWO) show promise for on site or off site PFAS degradation.

These integrated treatment systems may offer the flexibility needed to address site-specific conditions and the diverse chemical characteristics of PFAS. Successful treatment

train applications such as foam fractionation (FF) combined with IX ([Burns et al., 2021](#)), IX with plasma, and combinations of FF, IX, polymer adsorbents, hydrothermal alkaline treatment, and SCWO, have been demonstrated in the USA and other regions ([ESTCP, 2023](#); [2024](#); [ITRC, 2023](#); [Hao et al., 2023](#)). Other examples include NF with UV ([Liu et al., 2021](#)), FF combined with electrochemical oxidation (EO), and polishing resins ([Wang et al., 2023b](#)), IX and EO ([Liang et al., 2022](#)), and ozone and UV fractionation ([Dai et al., 2019](#)). Pairing nanofiltration with EO has shown potential for treating high PFAS concentrations, offering fast degradation rates and being relatively straightforward to integrate into existing treatment systems ([Lu et al., 2020](#)). While each method offers distinct advantages, they also have limitations, it is crucial to evaluate the most suitable combination based on the specific treatment needs and the characteristics of the contaminated matrix.

Although incineration remains a well-established disposal method for PFAS laden media, high costs and limited facility capacity highlight the potential need for pretreatment and volume reduction. Techniques such as coagulation/flocculation, membrane separation, and foam fractionation can concentrate PFAS before final destruction, potentially improving efficiency and cost effectiveness. Especially for wastewater that cannot be treated by GAC or XI. However, large scale implementation remains constrained by initial high costs, technical challenges, and energy requirements, particularly for smaller incineration facilities ([Franke et al., 2019b](#); [2019a](#)).

Also, the climate impacts, life cycle costs, and annual capital and operational expenditures differ substantially between available technologies. More research and the development of PFAS-specific life cycle assessment and life cycle cost approaches are likely needed to provide robust evidence for regulatory and investment decisions of different remediation methods ([Mendes et al., 2025](#)).

Overall, treatment trains may improve PFAS removal efficiency while minimising long term environmental and financial liabilities, making them a viable solution for complex contamination scenarios. However, while promising, more research is needed to consider factors such as technology compatibility, engineering constraints, climate impacts, and the operational and maintenance requirements. Along with necessary treatment volumes, flow rates, and discharge standards.

7. Conclusions on Remediation

This review illustrates the complexity of PFAS remediation; the technical, environmental and economic challenges involved. The chemical and thermal stability of PFAS, combined with their wide chemical diversity (functional groups, chain length, ionic state, hydrophobicity, solubility, volatility) and site-specific factors (geography, pH, temperature, dissolved organic matter/ions, and co-contaminants) can influence treatment performance. Complex mixtures and precursors that can partially transform during treatment further complicate achieving complete mineralisation. Analytical limitations also exist, as current monitoring focuses on around 50 analytes. While broader analytical techniques are emerging, they still require standardisation. Given these challenges, treatment effectiveness varies widely between technologies. Therefore, effective remediation of PFAS-contaminated sites will require tailored, site-specific approaches that account for local conditions, treatment limitations, and costs, supported by long-term monitoring.

High temperature incineration (HTI) is currently the only commercially viable method for large scale PFAS destruction, particularly for PFAS containing firefighting foams and other media. The effectiveness of incineration depends on PFAS chemical structure, waste type, incinerator design, and operating conditions. HTI can achieve near-complete mineralisation and PFAS destruction efficiencies of >99.99% for PFAS containing firefighting foams, when operated at 1,100°C, with a 2–3 second residence time in the secondary combustion chamber, sufficient turbulence, and properly balanced stoichiometry (waste, fuel, oxygen, and gas-phase components) ([Section 4.8](#)).

Emerging technologies including mechanochemical degradation, electrochemical oxidation, sonolysis, plasma, gasification/pyrolysis and supercritical water oxidation show potential to destroy PFAS and offer scalable, commercially viable solutions. Currently, most destructive methods are in pilot or laboratory stages and can only destroy PFAS in liquid phase. High costs, energy demands, potential by-product formation, scalability limitations, frequent maintenance requirements, limited familiarity with the technologies, and a lack of long-term field data currently hinder their widespread deployment. As such, these technologies are unlikely to replace existing methods in the short term and will require continued research and development to validate effectiveness and environmental performance. Widespread PFAS remediation will likely depend on developing cost-effective methods and evidence of complete mineralisation.

Sequestration is the most widely used method for PFAS removal from water and soil. Adsorption technologies such as granular activated carbon, ion exchange and membrane filtration are mature and can remove PFAS at large scale with high removal rates. However, they do not destroy PFAS, instead they transfer contaminants into concentrated waste streams that require additional treatment or secure disposal. The chemical diversity of PFAS complicates treatment, as many existing methods were developed for long-chain compounds. Short chain PFAS present ongoing challenges due to their high solubility and low sorption affinity, limiting the performance of many sequestration systems.

In the short to medium term optimising existing methods and a treatment train approach, combining separation and destruction technologies might be the most practical solution. These integrated systems can improve removal efficiency, reduce secondary waste and adapt to the diversity of PFAS contamination. To be effective, these systems must remain cost effective and adaptable to varying contaminant loads, volumes, and site-specific conditions.

Appendix A: Detailed Description of the Rapid Evidence Assessment Methodology

Developing a Search Strategy

A search strategy was developed using the PICO (Problem, Intervention, Comparison, Outcome) framework. Table 7 and 8 lists the PICO search protocols for the primary and secondary questions, respectively. This approach allowed for the creation of the three distinct research concepts based on the primary and secondary questions

Table 6. PICO (Problem, Intervention, Comparison, Outcome) search protocol for the primary question

Question Criteria	Main Term	Primary question PICO components
P: Problem	Population/species/habitat etc.	Environmental system contaminated with PFAS, what is the current state of knowledge regarding the optimal conditions required to effectively destroy PFAS from HWI regulated by the EA?
I: Intervention /Interest	What activity or approach is to be used? Why the interest	Temperature, residence times variations during incineration. Interest from EA, industry stakeholders, national government bodies, environmental scientists.
C: Comparison / Context	The main alternative, was a control used? What is the context	Control conditions (e.g. temperature, residence time, oxygen concentration). PFAS, a group of synthetic chemicals extensively employed in industrial and commercial sectors for many years, exhibit persistence in the environment and some bioaccumulation in organisms. The Environment Agency is responsible for regulating and permitting PFAS emissions from industrial sources such as HWI through specific permits.
O: Outcome/ Result	What are you trying to measure/accomplish ?	Determining optimal conditions for effectively destroying PFAS through incineration and improve our understanding/knowledge of the incineration of PFAS preventing further release of these chemicals into the environment.

Table 7. PICO (Problem, Intervention, Comparison, Outcome) search protocol for the secondary question

Question Criteria	Main Term	Secondary question PICO components
P: Problem	Population/species/habitat etc.	Environmental system contaminated with PFAS, what alternative remediation techniques are there for PFAS? And what are their effectiveness, feasibility and environmental impacts in destroying PFAS?
I: Intervention/Interest	What activity or approach is to be used? Why the interest	Various disposal methods. Interest from EA, industry stakeholders, national government bodies, environmental scientists.
C: Comparison/Context	The main alternative, was a control used? What is the context	Effectiveness and feasibility of different disposal methods.
O: Outcome/Result	What are you trying to measure/accomplish?	Comparative analysis of the effectiveness and feasibility of alternative disposal methods in destroying PFAS and improving our understanding/knowledge of PFAS remediation. Preventing further release of these chemicals into the environment by effectively managing them.

Developing the PICO Model and Boolean Search

The initial keyword search development was guided by the Source-Pathway-Receptor model (Appendix B) and the PICO framework (Appendix C). Keywords were strategically combined using Boolean operators (AND, OR) to create comprehensive search strings tailored to PFAS research. These strings served as the foundation for constructing detailed search filters.

Given the substantial volume of literature on PFAS, reflecting the increased awareness of their environmental and health risks, there was often an overwhelming number of irrelevant results or duplicate information. A focused search strategy was necessary. As of March 2024, a search in the Scopus database (Test 1, Appendix D) revealed over 117,000 peer-reviewed articles on PFAS, with approximately 9,000 papers published in 2023 alone. This highlights PFAS as emerging contaminants, with our understanding continuously evolving as new information becomes available.

Refining the PICO Model

To effectively manage this extensive literature, sensitivity testing was conducted to refine the search strings. This involved using different combinations of the PICO model and carefully crafted keywords to optimise results. Each search string yielded varying degrees of relevance to the research questions, as detailed in Appendix D. A qualitative review of the search results was performed to ensure alignment with the research objectives, culminating in a focused selection of information. The refined search strings were applied in Scopus, the primary scientific database for obtaining targeted peer-reviewed findings based on article titles and abstracts. This process resulted in “Test 20” (Appendix D), which narrowed the results to 1,272 citations by applying limits on publication date, language, and geographical region to improve relevance and manageability. This strategy optimised relevance and manageability.

Understanding the PFAS Research

VOSviewer software (version 1.6.18) ([Van Eck and Waltman, 2010](#)) was employed to generate network maps from terms in the titles and abstracts of literature searches conducted in Scopus. By using natural language processing algorithms, VOSviewer identified associations between terms and visualised them as network maps. This enabled the analysis of co-authorship, citation, and keyword co-occurrence networks, highlighting key researchers, influential papers, and emerging trends in PFAS incineration research. Also, keyword co-occurrence analysis revealed emerging trends and core themes related to PFAS incineration, simplifying complex data and offering a thorough view of the research.

Test 5 (Appendix D) produced a dataset of 193 publications focused on PFAS incineration, addressing the primary research question. Of the 2807 identified keywords, 218 met the threshold for inclusion in network maps, which were organised into four thematic clusters (**Figure 10**). These clusters represent the diversity of themes in PFAS incineration research. Key themes included environmental pollution and remediation (e.g., air and water pollution, remediation techniques), chemical properties and processes (e.g., adsorption, oxidation, degradation), and waste management strategies (e.g., landfill leachate and sewage treatment). This approach facilitated an in-depth examination of the literature, helping identify emerging trends and challenges related to PFAS destruction.

The four thematic clusters offer unique insights into PFAS research (**Figure 10**):

Cluster 1 (Red) focused on remediation techniques and environmental pollution, highlighted terms such as (waste incineration, pyrolysis, gas emissions, and climate change). These terms highlighted the importance of managing PFAS emissions and their contribution to air quality and climate change.

Cluster 2 (Green) concentrated on water and soil receptors, featuring keywords like (water pollutants, drinking water, and soil pollution) and source terms (effluents, foam). It also

connected to various remediation technologies, including (activated carbon, bioremediation, and ion exchange), indicating the diverse methods being explored to mitigate PFAS contamination in environmental receptors.

Cluster 3 (Blue) examined chemical processes involved in PFAS degradation, such as (oxidation, defluorination, and reaction kinetics). This cluster underscored the complexity of breaking down PFAS compounds like PFOA and other fluorocarbons, emphasising the need for continued research into effective degradation methods.

Cluster 4 (Yellow) addressed waste management challenges, incorporating terms related to (waste treatment, sewage biosolids, industrial waste, fly ash, waste disposal facilities, solid waste, leachate treatment). The focus on facilities handling waste and sewage biosolids underlined the critical role of managing PFAS-contaminated waste streams to prevent further environmental contamination.

These clusters collectively provide a thorough view of the current research on PFAS incineration, offering insights into ongoing challenges and future investigation areas. In addition, **Figure 11** illustrates the evolution of focus in the literature, with Clusters 1 and 3 spanning 2017–2019, Cluster 2 from 2020–2021, and Cluster 4 from 2021 onwards. This shift reflects a transition from early studies on PFAS incineration and chemical behaviour to more recent research on waste management and remediation strategies across different waste matrices.

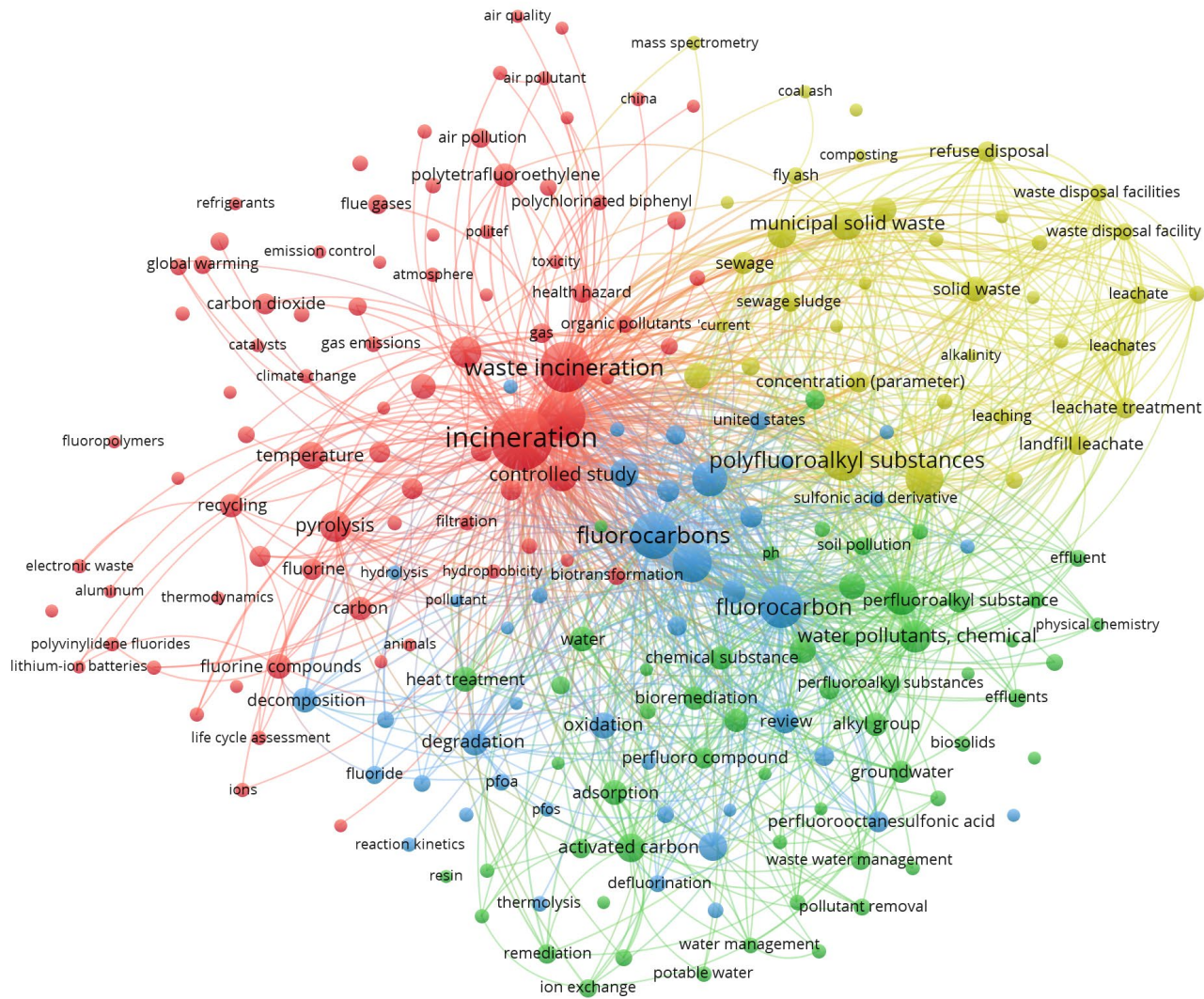


Figure 10. VOSviewer network map showing four clusters derived from Scopus data on reference titles and abstracts

Incorporating Grey Literature

Recognising the specialised nature of PFAS remediation and its emergence as a relatively new area of research, the significance of grey literature sources was acknowledged. Grey literature, encompassing papers, reports, newsletters, and web articles, was identified by the steering group and through searches across various platforms, including research and thesis databases, domestic and international government reports, and manual reviews of bibliographies from electronically sourced papers and internet search engines (Appendix E). Industry organisations were also contacted to inquire about any unpublished reports on PFAS incineration, ensuring a broad review that mitigates bias from solely relying on academic sources.

Reference Management

Zotero, a reference management software, was used to organise bibliographic data, research materials, and grey literature sources throughout the literature review process. For each search engine (Scopus and Google) and search string, a dedicated bibliography was generated and stored as an RIS file in Zotero. These RIS files captured a thorough record of all results obtained, ensuring efficient management and retrieval of relevant references throughout the review.

Study Review and Selection

Using the results from Test 20 (Appendix D), each study included in this review was examined to extract significant data directly relevant to the research questions. As mentioned above, this data was later categorised into three distinct research themes facilitating a comprehensive overview of current knowledge and findings within these domains. This systematic approach also enabled the identification of key research gaps that warrant further investigation. It is assumed that the studies analysed are free from significant errors and are suitable for informing recommendations related to this review.

A systematic approach was employed to select relevant papers for the literature review across three stages:

1. **First Pass Review:** Citations identified from the Scopus search were initially screened based on titles, abstracts, and publication types. Papers deemed irrelevant to the primary or secondary research questions were excluded. Studies that mentioned PFAS in general terms without specific keywords such as "incineration," "remediation," or "thermal treatment" were also discarded. Citations that raised uncertainties about relevance or had ambiguous titles were flagged for further assessment in the secondary review stage and retained in Zotero for detailed evaluation.

2. **Second Pass Review:** A more in-depth examination of the abstracts was conducted, and key papers were identified and saved in Zotero. Again, studies were excluded if they were irrelevant to the primary and secondary research questions. A criterion was applied: studies lacking clarity in their relevance to PFAS incineration or remediation, or those offering broad commentary without specific insights, were excluded from further review. The decision-making process for selecting studies based on titles and abstracts is illustrated in **Figure 12**.
3. **Third Pass Review:** The texts of the remaining papers were examined using a triage system to determine their significance, acknowledging that synthesising the full text of all studies in the final selection was not feasible. Priority was given to evidence reviews or studies that had already been summarised or critically assessed, especially those focusing on the optimal operational conditions for PFAS incineration, with particular attention to temperature and residence time. Studies discussing full-scale methods, innovative technologies, or new methods for PFAS remediation were also prioritised based on their relevance to the secondary research question.

Studies conducted in environments that closely simulate real-world industrial conditions, along with those supported by strong experimental data, were given the highest priority during the final review phase. Following this, all remaining studies were considered for inclusion. Given the relatively limited availability of grey literature sources and studies provided by the steering group, these were automatically incorporated into the third-pass review.

This systematic approach ensured that the final selection of papers represented the most relevant and impactful research findings related to PFAS destruction and remediation. The methodology and selection process, including the prioritisation criteria, are illustrated in **Figure 13**.

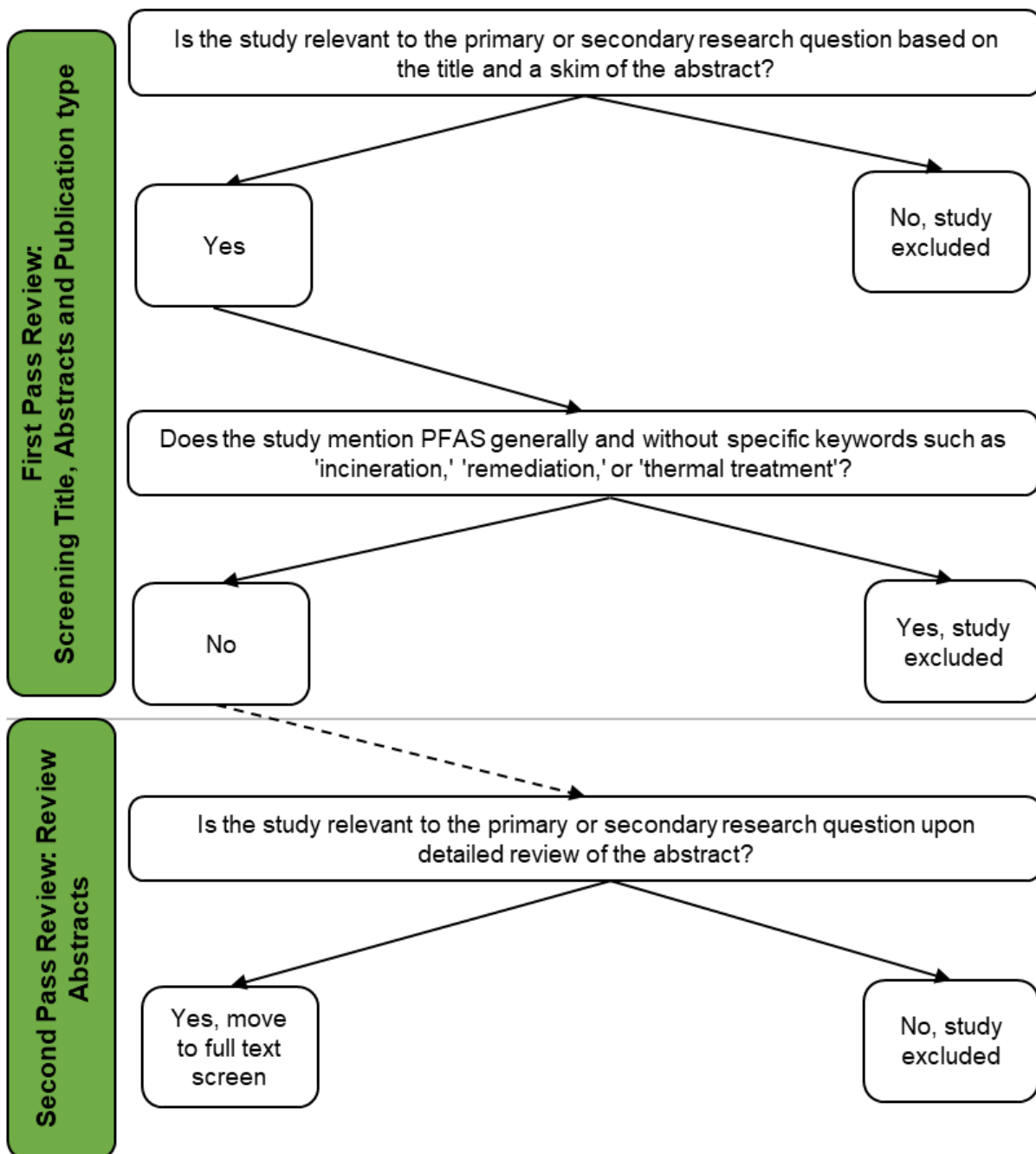


Figure 12. The decision-making process for study selection/screening during the first and second review phases

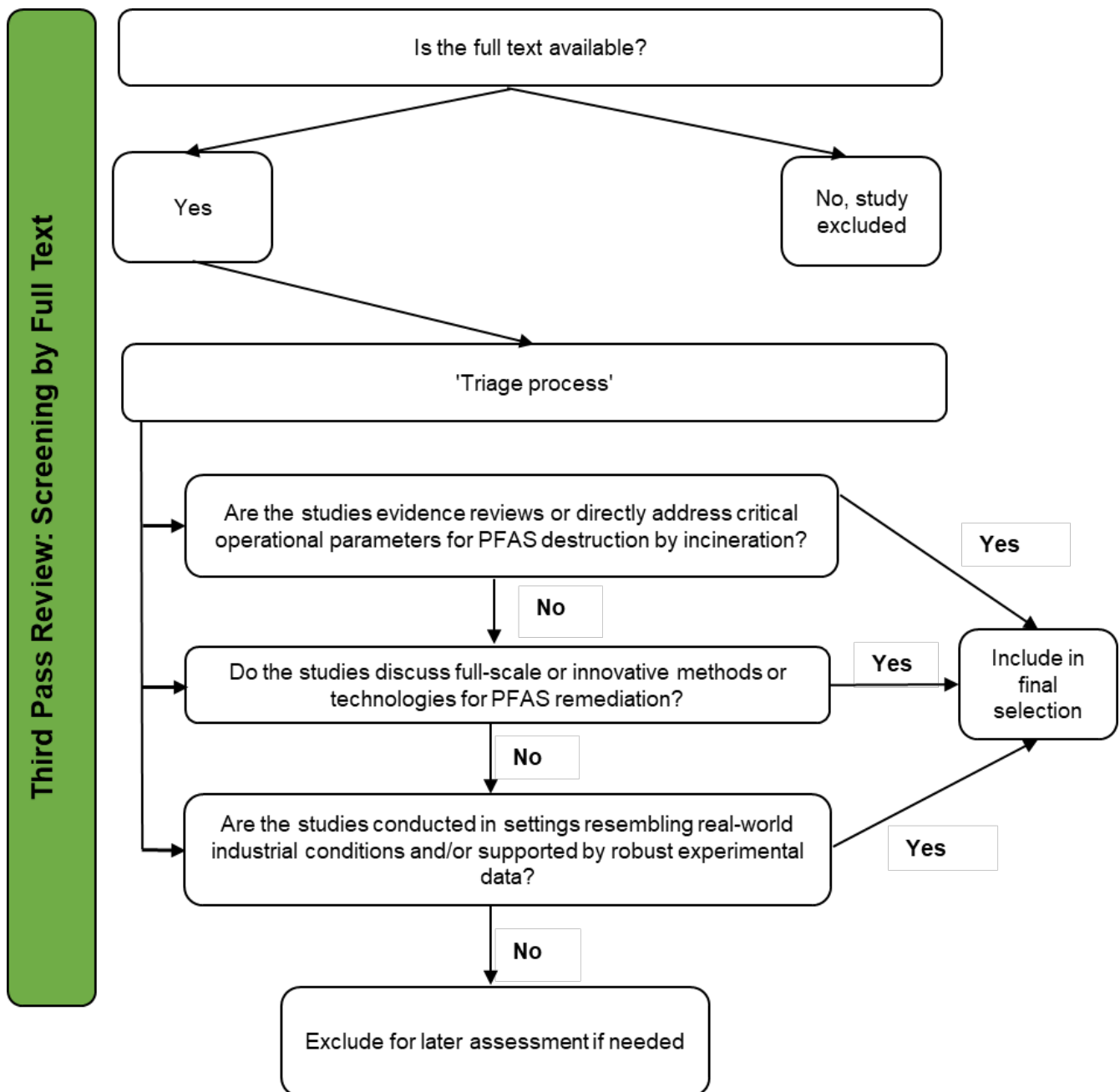


Figure 13. The study selection decision and triage process for the third pass review

Final Study Selection process

The study selection process, illustrated in **Figure 14**, commenced with the identification of 1,272 citations. Through the initial first and second pass reviews, 975 papers were excluded for failing to meet the inclusion criteria. The primary reasons for exclusion included a lack of relevance to the primary and secondary research questions and a general discussion of PFAS that did not incorporate specific keywords. Many of these excluded papers addressed topics such as the fate of PFAS in various matrices (e.g., wastewater, soil, consumer products), the synthesis and characterisation of inorganic materials for energy storage and catalysis, the development of energetic materials, and the applications of fluorinated polymers.

Following the initial reviews, 297 papers were identified as relevant to the primary question regarding optimal incineration conditions for PFAS destruction and the secondary question comparing PFAS disposal methods. In the successive third-pass review, these papers, along with 75 grey literature sources and additional studies provided by the steering group, underwent a comprehensive full-text screening and triage process. In total, 372 studies were evaluated during this phase.

From this selection, 232 studies were comprehensively examined, and relevant data was extracted for inclusion in this review. These studies provide valuable insights from research conducted across various regions, including the United States, China, Japan, Australia, Canada, and Europe. Additional papers were identified and provided by the steering group during the production of this review. These studies were then incorporated, bringing the total number of studies reviewed to over 300.

This systematic approach ensured that the final selection encompassed the most appropriate and impactful research findings, offering a comprehensive overview of current knowledge regarding PFAS incineration and remediation techniques. Regardless of the rapid nature of this review and its inherent limitations, the transparent methodology and structured processes employed provide a foundation for future research and advancements in understanding PFAS removal techniques.

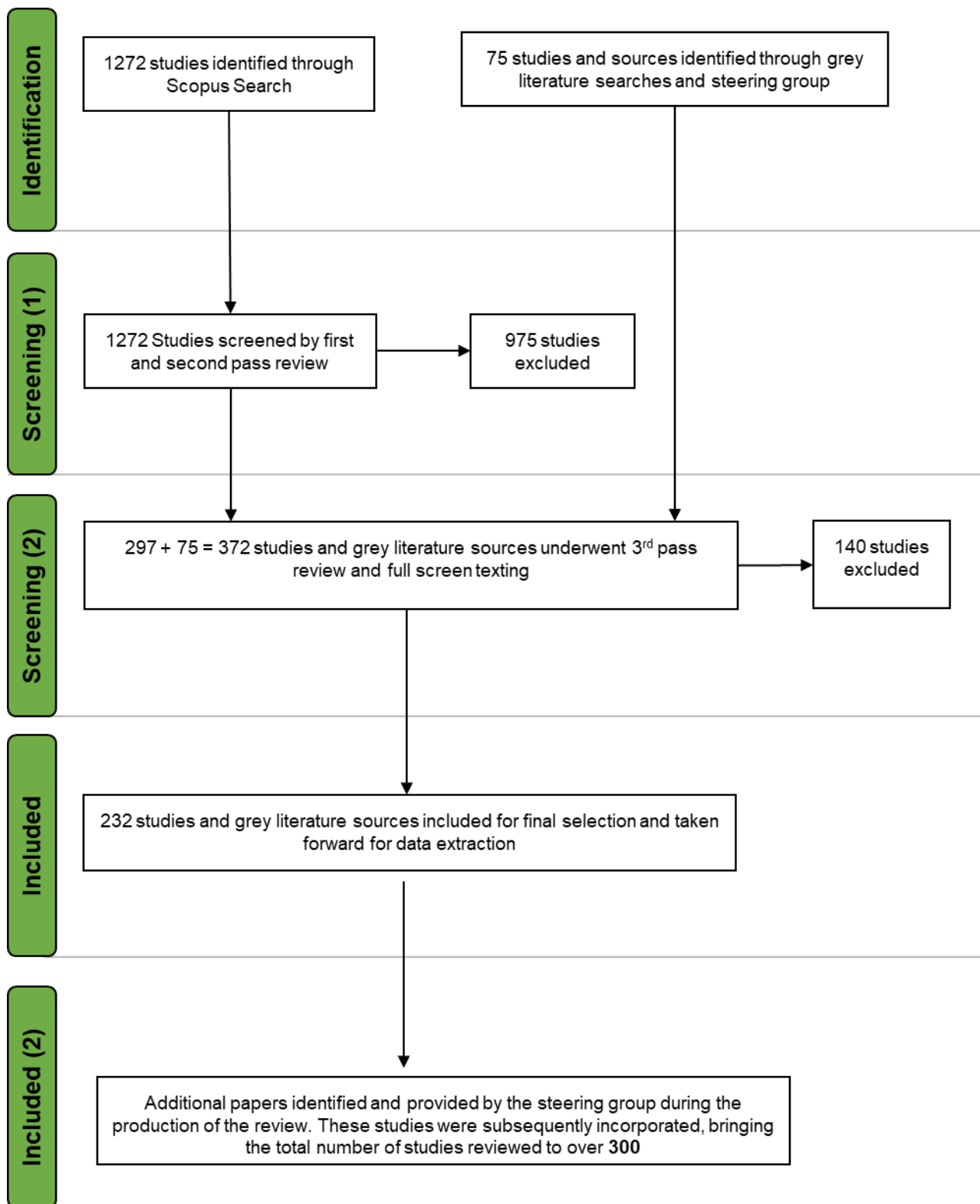


Figure 14. Selection process of studies analysed in the rapid evidence assessment

Study Strengths and Limitations

The findings presented in this report should be considered within the context of the following strengths and limitations

Strengths

- **Quasi-Systematic Approach:** The structured methodology improves the review's reliability
- **Comprehensive Search Strategy:** Utilisation of PICO concepts ensures a thorough examination of both peer-reviewed and grey literature
- **Transparent Reporting:** Clear methodologies and an efficient triage system promote reproducibility and streamline the review process
- **Strong Evidence Base:** Including diverse literature broadens the evidence base, while systematic categorisation of data increases credibility

Limitations

- **Rapid Review Constraints:** The nature of the review may result in insufficient time for thorough data extraction and synthesis, potentially affecting the depth of analysis and interpretation. Hence, the review provides a snapshot of the current understanding and serves as an overview rather than an exhaustive literature review.
- **Search Engine Dependence:** Relying on a single search engine may result in missing relevant studies due to limited advanced search functionalities
- **Selection Bias:** Exclusions based on access issues pose a risk of selection bias, potentially skewing findings
- **Lack of Bias Assessment:** The absence of risk of bias assessment for included studies could impact the review's reliability
- **Reviewer Subjectivity:** The reliance on a single reviewer for screening may introduce subjective interpretation
- **No traditional peer review process**
- **Industry Influence:** Economic interests of industry stakeholders may affect data availability and interpretation, especially in grey literature

Although the transparent methodology and systematic approach provide a foundation for future research on PFAS removal techniques. Addressing these limitations in subsequent reviews will strengthen the reliability and applicability of findings.

Appendix B

Table 8. Initial PICO search terms using Source, Pathway, Receptor model used to help develop a search string applied to a search of bibliographic databases (Scopus)

The source is represented by the contaminant of concern (PFAS), the primary pathway mechanism investigated comprised the incineration process (e.g. incineration/heat), and the receptor was the (destruction/ emission) of PFAS. This initial list of keywords served as the starting point for the targeted search strategy.

Source or Contaminant Term	Pathway	Receptor or End-point Term
PFAS	Incinerat*	Air
PFOA	Combust*	Emission
PFOS	Heat	Gaseous
AFFF	Thermal	Destruction
Per- and polyfluoroalkyl substances	Plasma	Analy*
HWI	Waste	Concentration

Search keywords were amalgamated using relevant Boolean operators like AND and OR, with parentheses ensuring the correct order of operations. For example, initial queries such as:

(PFAS OR fluoroalkyl) AND (Incinerat*) (PFAS OR fluoroalkyl)

AND (Incinerat*) OR (Combust*)

Were run to gauge the volume of literature available. These queries aimed to identify articles relevant to the primary question of the evidence synthesis during the initial scoping phase

Appendix C

Table 9. PICO keyword search terms

Population	Intervention Mechanism	Comparator
PFAS	Incinerat* (Incineration, Incinerator, etc.)	Alternative disposal method*
PFOA	Thermal	Landfill disposal
PFOS	High-temperature treatment	Biological treatment
AFFF	Hazardous waste incinerat*	Adsorption
Firefighting foam*	Pyrolysis	Filtration
Fluorinated foam*	Gasification	Precipitation
Foam-based PFAS contamin*	Plasma treatment	Membrane process*
PFAS contamin* in fire suppression agent*	Chemical oxidation	Chemical degradation
HWI	Combust*	Advanced oxidation process*
United States Environmental Protection Agency	High-temperature destruction	Sorption
USEPA	Thermal destruction	Coagulation
		Electrochemical treatment
		Chemical treatment
		Landfilling

Appendix D

Table 10. provides a comprehensive overview of all search terms used in Scopus on 28th of March 2024, along with the corresponding number of results obtained. The initial search strategy involved constructing an inventory of keywords and modules by referencing the OECD list of known PFAS and keywords/concepts from Appendix B and C. Sensitivity testing involved adjusting and refining the search strategy using different combinations of the PICO modules to optimise results. A qualitative assessment and sensitivity test were conducted on the strategy, and the search string was refined to determine the best fit of results with the research question. The optimal search string, "Test 20," was selected for the review, yielding 1,272 reference papers.

Table 10. The search string used in Scopus on the 28th of March 2024

Test Number	Search String	No. of Results
Concept 1 Optimal operations conditions for PFAS incineration		
Test 1	PFAS* OR polyfluoroalkyl* OR perfluoroalkyl* OR fluorochemical* OR fluorosurfactant* OR "perfluoroalkyl carbo*" OR PFCA* OR "perfluoroalkane sulf*" OR PFSA* OR xFASA* OR xFASE* OR SAmPAP* OR "perfluoroalkyl phosph*" OR PFPA* OR PFPiA* OR (*perfluoro* AND *phosphinyl*) OR PFPiAM* OR "perfluoroalkane disulf*" OR *fluorotelomer* OR "perfluoroalkyl iodide*" OR PFAI* OR FTOH* OR (*fluorotelomer* AND "phosphate ester*") OR FTSA* OR FTCA* OR FTAL OR "perfluoroalkyl diiodide*" OR "**fluoroalkyl ether*" OR "**fluoroalkyl alkane*" OR PFECA* OR PFESA* OR (*fluoroether* AND *alkene*) OR PFAA* OR "perfluoroalkyl silane*" OR "perfluoroalkyl alcohol*" OR perfluoroalkane* OR perfluoroalkene* OR "perfluoroalkyl amine*" OR "perfluoroalkyl epoxide*" OR "perfluoroalkyl keton*" OR "perfluoroalkyl halide*" OR "perfluoroalkyl radical*" OR "perfluoroalkyl cyanide" OR "perfluoroalkyl metal" OR "perfluoroalkyl thiol" OR "perfluoroalkyl sulfide" OR PFAA* OR hydrofluorocarbon* OR "semifluorinated alkane*" OR hydrofluoroether* OR hydrofluoroolefin* OR "semi-fluorinated keton*" OR "side-chain fluorinated aromatic*" OR fluoropolymer* OR polytetrafluoroethylene OR PTFE OR "polyvinylidene fluoride" OR PVDF OR "fluorinated ethylene	117,185

Test Number	Search String	No. of Results
	propylene" OR "perfluoralkoxyl polymer" OR "polyvinyl fluoride" OR "ethylene tetrafluoroethylene" OR ETFE OR "VDF-HFP" OR PCTFE OR "oxetane polymer" OR "perfluorobutyric acid*" OR PFBA* OR "perfluoropentanoic acid*" OR PFPeA* OR "perfluorohexanoic acid*" OR PFHxA* OR "perfluoroheptanoic acid*" OR PFHpA* OR "perfluorononanoic acid*" OR PFNA* OR "perfluorodecanoic acid*" OR PFDA* OR "perfluoroundecanoic acid*" OR PFUnDA* OR "perfluorododecanoic acid*" OR PFDODA* OR "perfluorotridecanoic acid*" OR PFTrDA* OR "perfluorotetradecanoic acid*" OR PFTeDA* OR (*perfluorobutane* AND **sulfonic acid**) OR PFBS* OR (*perfluoropentane* AND **sulfonic acid**) OR PFPeS* OR (*perfluorohexane* AND **sulfonic acid**) OR PFHxS* OR (*perfluoroheptane* AND **sulfonic acid**) OR PFHpS* OR (*perfluorononane* AND **sulfonic acid**) OR PFNS* OR (*perfluorodecane* AND **sulfonic acid**) OR PFDS* OR (*methyperfluorooctanesulfonamido* AND "acetic acid") OR MeFOSAA* OR ("n-ethylperfluorooctane*" AND **sulfonamidoacetic acid**) OR *EtFOSAA* OR "fluorotelomer sulfonic acid*" OR "6:2 FTSA*" OR "8:2 FTSA*" OR (*heptafluoropropoxy* AND **propanoic acid**) OR "hexafluoropropylene oxide dimer acid" OR "HFPO-DA*" OR "GenX*" OR (*tetrafluoro* AND *hexafluoro* AND *perfluoropropoxy* AND *propoxy* AND **propanoic acid**) OR "HFPO-TA*" OR (*tetrafluoro* AND *hexafluoro* AND *tetrafluoroethoxy* AND *propan* AND **oxypropanoic acid**) OR "Hydro-Eve*" OR (*tetrafluoro* AND *hexafluoro* AND *tetrafluoroethoxy* AND *propan* AND **oxyethanesulfonic acid**) OR "Nafion Byproduct 2" OR (*dioxa* AND **perfluorononanoic acid**) OR ADONA* OR (*perfluoro* AND "butaoxadecanoic acid") OR "PFO4DA*" OR (*perfluoro* AND **pentaoxidodecanoic acid**) OR "PFO5DoDA*" OR **polyfluorinated ether sulfon** OR "6:2 Cl-PFESA*" OR "8:2 Cl-PFESA*"	
Test 2	Test 1 AND "Waste" OR "landfill" OR "leachate" OR "incinerat*" OR "recycling" OR "disposal"	4157
Test 3	Test 1 AND Inciner* OR Combust*	1204
Test 4	Test 1 AND Inciner* AND Hazardous OR Waste	15
Test 5	Test 1 AND Inciner*	193
Test 6	Test 1 AND Inciner* AND High AND temp*	48

Test Number	Search String	No. of Results
Test 7	Test 1 AND incinerat* OR combust* AND (residence time OR temperature)	15
Test 8	Test 1 AND incinerat* OR combust* AND (United States Environmental Protection Agency OR USEPA)	7
Test 9	Test 1 AND incinerat* OR combust* AND (destruction efficiency OR cost effectiveness)	3
Test 10	Test 1 AND incinerat* OR thermal treatment OR combust* OR High temperature Destruction OR thermal oxidation OR thermal destruction AND (residence time OR temperature)	5
Concept 2: Comparative Analysis of PFAS remediation methods		
Test 11	Test 1 AND incinerat* OR thermal treatment OR combust* OR High temperature Destruction OR thermal oxidation OR thermal destruction	41
Test 12	Test 1 AND ("alternative disposal" OR "remediation methods")	1
Test 13	Test 1 AND ("disposal" OR "remediation " OR " Cleanup AND approaches " OR " decontamination AND strategies " OR " environmental AND restoration AND methods " OR " emerging AND technologies	20
Test 14	Test 1 AND " ("alternative disposal" OR "remediation methods" OR "treatment techniques" OR "cleanup approaches" OR "decontamination strategies" OR "environmental restoration methods") AND (incineration OR "thermal treatment" OR "high-temperature treatment" OR combustion OR pyrolysis OR gasification OR "plasma treatment" OR "chemical oxidation" OR "advanced oxidation processes" OR bioremediation OR phytoremediation OR "electrochemical treatment" OR adsorption OR filtration OR "ion exchange" OR "membrane separation") AND (effectiveness OR efficiency OR efficacy)	38

Test Number	Search String	No. of Results
Test 15	Test 1 AND incinerat* OR thermal treatment OR combust* OR High temperature Destruction OR thermal oxidation OR thermal destruction OR plasma treatment OR Pyrolysis OR Hazardous Waste Incinerat*	9
Test 16	(Test 1) AND (Fluorinated foam* OR "Foam-based PFAS contamin*" OR "PFAS contamin* in fire suppression agent*") AND (Incinerat* OR "Hazardous waste incinerat*" OR Pyrolysis OR Gasification OR "Thermal treatment" OR "Hightemperature treatment" OR "Plasma treatment" OR "Chemical oxidation" OR Combustion OR "High-temperature destruction") AND ("Alternative disposal method*" OR "Landfill disposal" OR "Biological treatment" OR Adsorption OR Filtration OR Precipitation OR "Membrane process*" OR "Chemical degradation" OR "Advanced oxidation process*" OR Sorption OR Coagulation OR "Electrochemical treatment")	792
Test 17	Test 1 AND alternative AND disposal OR remediation OR "treatment technology" adsorption AND oxidation "chemical degradation" "biological degradation" "chemical oxidation" "activated carbon" "ion exchange" bioremediation AND pyrolysis	116
Concept 3: Environmental Impact Assessment of PFAS Disposal Methods		
Test 18	Test 1 AND incinerat* OR combust* AND environmental impacts OR health risks	20
Test 19	Test 1 incinerat* OR "alternative disposal") AND (environmental OR emissions OR byproducts OR "ecosystem impacts"	48
Test 20	COMBINATION OF TEST 1, TEST 3, TEST 14, TEST 16 and TEST 19 PFAS* OR polyfluoroalkyl* OR perfluoroalkyl* OR fluorochemical* OR fluorosurfactant* OR "perfluoroalkyl carbo*" OR PFCA* OR "perfluoroalkane sulf*" OR PFSA* OR xFASA* OR xFASE* OR SAmPAP* OR "perfluoroalkyl phosph*" OR PFPA* OR PFPiA* OR (*perfluoro* AND *phosphinyl*) OR PFPiAM* OR "perfluoroalkane disulf*" OR *fluorotelomer*	1272

Test Number	Search String	No. of Results
	<p>OR "perfluoroalkyl iodide*" OR PFAI* OR FTOH* OR (*fluorotelomer* AND "phosphate ester*") OR FTSA* OR FTCA* OR FTAL OR "perfluoroalkyl diiodide*" OR "**fluoroalkyl ether*" OR "**fluoroalkyl alkane*" OR PFECA* OR PFESA* OR (*fluoroether* AND *alkene*) OR PFAA* OR "perfluoroalkyl silane*" OR "perfluoroalkyl alcohol*" OR perfluoroalkane* OR perfluoroalkene* OR "perfluoroalkyl amine*" OR "perfluoroalkyl epoxide*" OR "perfluoroalkyl keton*" OR "perfluoroalkyl halide*" OR "perfluoroalkyl radical*" OR "perfluoroalkyl cyanide" OR "perfluoroalkyl metal" OR "perfluoroalkyl thiol" OR "perfluoroalkyl sulfide" OR PFAA* OR hydrofluorocarbon* OR "semifluorinated alkane*" OR hydrofluoroether* OR hydrofluoroolefin* OR "semi-fluorinated keton*" OR "side-chain fluorinated aromatic*" OR fluoropolymer* OR polytetrafluoroethylene OR PTFE OR "polyvinylidene fluoride" OR PVDF OR "fluorinated ethylene propylene" OR "perfluoroalkoxy polymer" OR "polyvinyl fluoride" OR "ethylene tetrafluoroethylene" OR ETFE OR "VDF-HFP" OR PCTFE OR "oxetane polymer" OR "perfluorobutyric acid*" OR PFBA* OR "perfluoropentanoic acid*" OR PFPeA* OR "perfluorohexanoic acid*" OR PFHxA* OR "perfluoroheptanoic acid*" OR PFHpA* OR "perfluorononanoic acid*" OR PFNA* OR "perfluorodecanoic acid*" OR PFDA* OR "perfluoroundecanoic acid*" OR PFUnDA* OR "perfluorododecanoic acid*" OR PFDoDA* OR "perfluorotridecanoic acid*" OR PFTrDA* OR "perfluorotetradecanoic acid*" OR PFTeDA* OR (*perfluorobutane* AND "**sulfonic acid*") OR PFBS* OR (*perfluoropentane* AND "**sulfonic acid*") OR PFPeS* OR (*perfluorohexane* AND "**sulfonic acid*") OR PFHxS* OR (*perfluoroheptane* AND "**sulfonic acid*") OR PFHpS* OR (*perfluorononane* AND "**sulfonic acid*") OR PFNS* OR (*perfluorodecane* AND "**sulfonic acid*") OR PFDS* OR (*methylerfluorooctanesulfonamido* AND "acetic acid*") OR MeFOSAA* OR (*n-ethylperfluorooctane*" AND "**sulfonamidoacetic acid*") OR *EtFOSAA* OR "fluorotelomer sulfonic acid*" OR "6:2 FTSA*" OR "8:2 FTSA*" OR (*heptafluoropropoxy* AND "**propanoic acid*") OR "hexafluoropropylene oxide dimer acid" OR "HFPO-DA*" OR "GenX*" OR (*tetrafluoro* AND *hexafluoro* AND *perfluoropropoxy* AND *propoxy* AND "**propanoic acid*") OR "HFPO-TA*" OR (*tetrafluoro* AND *hexafluoro* AND *tetrafluoroethoxy* AND *propan* AND "**oxypropanoic acid*") OR "Hydro-Eve*" OR (*tetrafluoro* AND *hexafluoro* AND *tetrafluoroethoxy* AND *propan* AND "**oxyethanesulfonic acid*") OR "Nafion Byproduct 2" OR (*dioxa* AND "**perfluorononanoic acid*") OR ADONA* OR (*perfluoro* AND "butaoxadecanoic acid*") OR "PFO4DA*" OR (*perfluoro* AND "**pentaoadodecanoic acid*") OR "PFO5DoDA*" OR "**polyfluorinated ether sulfon*" OR "6:2 CI-PFESA*" OR "8:2 CI-PFESA*"</p> <p>AND</p>	

Test Number	Search String	No. of Results
	<p>inciner* OR combust*</p> <p>OR</p> <p>("alternative disposal" OR "remediation methods" OR "treatment techniques" OR "cleanup approaches" OR "decontamination strategies" OR "environmental restoration methods") AND (incineration OR "thermal treatment" OR "high-temperature treatment" OR combustion OR pyrolysis OR gasification OR "plasma treatment" OR "chemical oxidation" OR "advanced oxidation processes" OR bioremediation OR phytoremediation OR "electrochemical treatment" OR adsorption OR filtration OR "ion exchange" OR "membrane separation") AND (effectiveness OR efficiency OR efficacy)</p> <p>OR</p> <p>("Fluorinated foam*" OR "Foam-based PFAS contamin*" OR "PFAS contamin* in fire suppression agent*") AND (incinerat* OR "hazardous waste incinerat*" OR pyrolysis OR gasification OR "thermal treatment" OR "high-temperature treatment" OR "plasma treatment" OR "chemical oxidation" OR combustion OR "hightemperature destruction") AND ("alternative disposal method*" OR "landfill disposal" OR "biological treatment" OR adsorption OR filtration OR precipitation OR "membrane process*" OR "chemical degradation" OR "advanced oxidation process*" OR sorption OR coagulation OR "electrochemical treatment")</p>	
Test 21	Test 20 AND ("environment* OR emission* OR byproduct* OR "ecosystem impact*")	454

Appendix E

- Internet web browsers such as Google using the advanced search function and DuckDuckgo
- Gov.uk
- Sepa.org.uk
- Barbour Comprehensive
- EThOS, an e-theses online service hosted by the British Library
- Open Access Theses and Dissertations
- DART-Europe, an e-theses portal
- NERC library service
- National academies press
- Science magazine
- European Chemicals Agency website
- The OpenGrey.EU grey literature database
- Data archiving and networked services database

Studies that appeared relevant based on their title and abstract were deemed eligible and subsequently included in the screening selection

Table 11. Search terms for online search engines and grey literature sources from the 20th of April to 5th of May

Search 1: "PFAS OR PFOA OR PFOS AND remediation"	Search 6:" PFAS AND PFOA AND waste management"
Search 2: " PFAS AND PFOA AND disposal methods"	Search 7:" PFAS AND PFOA AND pollution control"
Search 3:" PFAS AND PFOA AND treatment techniques"	Search 8:" PFAS AND PFOA AND regulation"
Search 4:" PFAS AND PFOA AND incineration"	Search 9:" PFAS AND PFOA AND contamination"
Search 5:" PFAS AND PFOA AND environmental impact"	Search 10:" PFAS AND PFOA AND cleanup"

These diverse sources of grey literature played a key role in minimising bias in the search strategy by providing evidence beyond traditional academic electronic bibliographic sources, ensuring a more comprehensive and balanced assessment of the available literature on PFAS remediation techniques.

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Glossary

Adsorption: Adsorption is the process where molecules from a gas, liquid, or dissolved solid adhere to the surface of a solid material. This process is often used in environmental remediation to remove pollutants from water or air.

Anionic PFAS: PFAS compounds that carry a negative charge

Bed Volumes (BV): This term relates to the capacity and performance of a filter bed, often used in conjunction with IX resins. One bed volume is equivalent to the volume of water that fills the empty filter bed.

Bioaccumulate: The accumulation of a substance, such as a toxic chemical, in various tissues of a living organism.

Biomagnify: Through food chains, whereby organisms at higher trophic levels accumulate greater concentrations

Biosolids: Biosolids are the nutrient-rich organic materials resulting from the treatment of sewage biosolids. They can be used as fertilisers but may contain PFAS due to their presence in wastewater. Concerns regarding PFAS in biosolids highlight the need for careful management and potential treatment before application on land.

Boolean search: Uses specific words and symbols known as Boolean operators (e.g., AND, OR) alongside keywords to limit or expand search results.

Branched Isomer: A branched isomer is a chemical structure in which at least one carbon atom is bonded to more than two other carbon atoms, resulting in a branching of the carbon backbone. Within a homologous series of compounds with the same carbon count, multiple isomers with varying branching arrangements can exist.

Catalysts: Substances that increase the rate of a chemical reaction without being consumed in the process. Catalysts can influence degradation efficiency during incineration

Cationic PFAS: PFAS compounds that carry a positive charge

Co-contaminants: Additional pollutants present in a contaminated site along with PFAS, which can affect the performance of remediation technologies

Combustion: Combustion is a complex sequence of chemical reactions between a substance (fuel) and an oxidising agent that releases heat, and results in a (limited) number of combustion reaction products

Defluorination: The removal of fluorine atoms from a chemical compound.

Exotoxicity: is the negative impact of a substance or activity on a population of animals, plants, or microbes in the environment.

Empty Bed Contact Time (EBCT): This is a crucial parameter in water treatment processes, particularly when using filtration systems like granular activated carbon (GAC) or ion exchange (IX) resins. EBCT refers to the amount of time water is in contact with the treatment media in a filter bed.

Environmental Compartments: Air, water, soil, and flora and fauna, that is, living organisms.

Environmental Quality Standards (EQS): EQS are legally enforceable limits on the concentrations of pollutants allowed in environmental compartments like water, soil, or air. These standards are set to protect human health and the environment.

Ex situ: Refers to the treatment or remediation of contamination after it has been removed from its original location, such as excavating contaminated soil and treating it at a dedicated facility. Several PFAS treatment technologies, including incineration and some sorption methods, are typically conducted *ex situ*.

Fluorotelomerisation: Fluorotelomerisation is a chemical process used to synthesise fluorinated organic compounds, including certain types of PFAS.

Functional group: A functional group is a specific group of atoms within a compound that is responsible for some of the physiochemical characteristics of the compound. Functional groups are used to classify organic molecules into distinct families, such as alcohols, ketones, or carboxylic acids.

Halogenated organic substances: Halogenated organic substances are organic compounds where one or more hydrogen atoms have been replaced by halogen atoms (fluorine, chlorine, bromine, or iodine). PFAS fall under this category due to their carbon-fluorine bonds.

Headgroup: The headgroup is the hydrophilic part of a molecule, containing one or more functional groups (e.g., carboxylic acid or sulfonic acid) attached to a relatively long aliphatic tail or backbone. In PFAS, the headgroup influences solubility, reactivity, and environmental behaviour.

In situ: Refers to the treatment or remediation of contamination in its original location, without excavating or removing the contaminated material. Several PFAS remediation techniques, such as soil stabilisation and some sorption methods, can be applied *in situ*.

Isomer: Molecules with same molecular formulas, but different arrangement of atoms

Landfill: A method of getting rid of very large amounts of rubbish by burying it in a large deep hole.

Mineralisation: Mineralisation is the complete breakdown of organic compounds into inorganic substances like carbon dioxide, water, and salts. In the context of PFAS remediation, mineralisation is the desired outcome, as it represents the destruction of the harmful PFAS compounds.

Monomer: A molecule that binds to other molecules to form a polymer

Non polymeric PFAS: A class of PFAS that do not have a polymeric structure. These compounds are typically smaller, mobile, and more persistent in the environment compared to polymeric PFAS. Non-polymeric PFAS are widely used in industrial applications and consumer products, often as processing aids or surfactants, and have been linked to environmental contamination and bioaccumulation concerns.

Organofluorine: Organofluorine compounds are organic compounds containing a carbon-fluorine bond. PFAS belong to this larger group of compounds.

Perfluoroalkyl chain: A perfluoroalkyl chain is a chain of carbon atoms where all the hydrogen atoms have been replaced by fluorine atoms. These chains are a key structural feature of PFAS and contribute to their stability and persistence in the environment.

Polytetrafluoroethylene (PTFE): PTFE, commonly known as Teflon, is a synthetic fluoropolymer. While PTFE itself is largely considered inert, the sources highlight concerns related to its potential degradation into harmful PFAS during manufacturing, use, or disposal.

Precursors: Precursors are substances that are transformed into other substances during a chemical reaction. In the context of PFAS, precursors are compounds that can degrade or break down into PFAS under specific conditions. Understanding the role of precursors is crucial for managing PFAS, as they can be indirect sources of contamination.

PICs: PICs are a complex mixture of chemicals formed during the incomplete combustion of organic materials. In the context of PFAS incineration, PICs are a concern as they may include harmful substances, and their formation should be minimised through optimised incineration conditions.

REACH: REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) is a European Union regulation that aims to protect human health and the environment from the risks posed by chemicals, since assimilated to UK REACH.

Remediation: The process of removing, reducing, or neutralising contaminants from soil, water, air, or waste to protect human health and the environment. Methods include

physical, chemical, biological, and thermal treatments to restore affected areas and prevent further pollution.

Residence time: Residence time, in the context of incineration, refers to the duration that waste materials are exposed to high temperatures within the combustion chamber. Ensuring sufficient residence time is crucial for the effective destruction of PFAS and other contaminants during incineration.

Rotary Kiln: A rotating cylindrical furnace used in industrial processes, including hazardous waste incineration. The rotating action helps to mix the waste and ensure complete combustion.

Scopus: An abstract and citation database launched by the academic publisher Elsevier.

Serum: Serum is the clear fluid in blood, remaining after clotting, containing proteins, electrolytes, hormones, and antibodies, used in health and exposure assessments.

Source-Pathway-Receptor Model: A conceptual framework used in environmental science to understand the movement of contaminants from their source through various pathways to potential receptors. In the context of PFAS, this model helps to identify potential sources of PFAS, pathways of contamination, and populations or ecosystems at risk.

Sorption: A physical or chemical process in which one substance takes up or holds another.

Stockholm Convention: The Stockholm Convention is a global treaty to protect human health and the environment from persistent organic pollutants (POPs) and came into force in May 2004.

Surfactant: A surfactant is a substance that reduces surface tension, often used in detergents and cleaning products to improve their effectiveness. PFAS, due to their unique properties, can act as surfactants in firefighting foams.

Surrogates: Substances used as indicators for the presence or behaviour of other compounds that are difficult to measure directly. In the context of PFAS incineration, surrogates with varying properties are recommended to monitor the destruction efficiency of a range of PFAS compounds.

Thermal treatment: Thermal treatment refers to processes that use high temperatures to treat waste materials. Such as smouldering combustion, pyrolysis, gasification, hydrothermal carbonisation/liquefaction, and incineration. In the context of PFAS, thermal treatment methods, such as incineration, are explored as potential options for destroying these persistent compounds.

Treatment Train: A sequence of treatment processes used to remove contaminants from water or waste streams. In the context of PFAS, a treatment train might involve a combination of sequestration (concentration) and destruction technologies.

Turbulence: Turbulence, in the context of incineration, refers to the mixing of gases and waste materials within the combustion chamber. Adequate turbulence ensures efficient heat transfer and contact between the waste and high temperatures, enhancing the destruction of contaminants like PFAS.

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