Review of Strategies to Control Air Pollution due to PFAS

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Abstract. Per and polyfluoroalkyl substances (PFAS), also known as "forever chemicals" have emerged as the next environmental threat due to their persistence and challenges in capture and control. The water contamination aspect of the PFAS has been extensively researched, however, the emissions into the atmosphere are a growing concern due to their volatility, long-range transport potential, and resistance to degradation. As a result of discovery of air pollution pathways of PFAS due to industrial processes, consumer usage and waste treatment, researchers have been identifying innovative technologies to mitigate the PFAS related air pollution. This study reviews various types of existing technologies such as oxidation, absorption and adsorption. In addition, a review of emerging technologies such as non-thermal plasma treatment was also investigated and presented in this study. Key research gaps and opportunities for future innovation were identified and possibilities of multi-prong approach were investigated to mitigate PFAS associated air pollution.

1 Introduction

PFAS are a large group of fluorinated organic chemicals, frequently referred as "forever chemicals" are used extensively due to their thermal and chemical stability. The history of PFAS goes back to 1940s when these chemicals were developed and used in Teflon®, firefighting foams and stain-resistant products. Around 2000s, the US Environmental Protection Agency (EPA) began investigating PFAS contamination triggered by internal documents from 3M and DuPont and water contamination findings in West Virginia. By 2002, 3M voluntarily phased out perfluorooctane sulfonic acid (PFOS) in the US and in 2009, the PFOS and perfluorooctanoic acid (PFOA) were added to the Stockholm Convention on Persistent Organic Pollutants [1] for global regulation and the US EPA issued the provisional health advisories. In 2016, the US issued PFOA and PFOS Drinking Water Health Advisories [2]. In 2021, The EPA Council on PFAS was established with a mandate to develop a wholistic approach to protect the public health and the environment from the impacts of PFAS. The PFAS Council developed the PFAS Strategic Roadmap [3]

While there was a significant amount of research on PFAS impacts associated with water, the air impact pathways and effects were not known until 2001 when PFAS was suspected in the ambient air near the DuPont facility in Parkersburg, WV. Between 2005-2007, studies

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began identifying fluorotelomer alcohols (FTOHs) and sulfonamides in indoor and outdoor air. These volatile category precursors are suspected to transform into persistent PFAS in the environment and can travel long distances. During the years 2008 – 2010, PFAS was detected in Arctic and remote locations thereby proving the long-range atmospheric transportation characteristics [4]. By 2015, US EPA formally established the air-to-soil and air-to-water pathways. The awareness about airborne PFAS and associated impacts has evolved since then and lead to the establishment of the Office of Air and Radiation by the US EPA PFAS Council.

2 Sources of PFAS Air Emissions

In order to understand the control and mitigation strategies, it would be prudent to review the sources of the PFAS species. Like other air pollutants, the airborne PFAS can originate from a variety of point and area sources. The following are some of the known PFAS sources:

- Industrial Manufacturing and Processing
    - Fluoropolymer synthesis: Polymerization can release volatile PFAS (PFAAs, FTOHs, sulfonamide precursors).
    - Surfactants/repellents production: Dryers, exhaust stacks, and formulation tanks in textiles, carpets, and paper manufacturing emit mixed PFAS species.
    - Fluorochemical handling: Blending, milling, and transfers generate fugitive emissions from powders and liquids.
- Thermal Treatment of Waste
    - Hazardous waste incineration: Insufficient temperature or residence time leads to partial PFAS destruction, forming ultrashort-chain acids and byproducts (e.g., HF, COF_2).
    - Sludge drying & biosolids incineration: PFAS in municipal/industrial sludge volatilize during drying/combustion.
    - Thermal desorption units (TDUs): Incomplete destruction can volatilize PFAS precursors from contaminated soils.
    - Metal smelting & aluminum casting: Fluorinated fluxes/coatings release PFAS vapors during melting and burnout.
- Product Use and Degradation
    - Use-phase volatilization & weathering: Heat, abrasion, and UV promote release of precursors (e.g., FTOHs) from treated products; atmospheric oxidation converts these to terminal PFAAs.

3 Fate and Transport of PFAS in the Atmosphere

The physical forms in atmosphere, transformation, transport mechanism and environmental distribution after deposition constitutes the fate and transport of PFAS in the atmosphere. In the atmosphere, PFAS can occur in gas and particle phases, or other aerosols suspended in the air. The gaseous phase includes volatile and semi-volatile compounds such as FTOHs and perfluoroalkane sulfonamides (FASAs). Ionic PFAS such as PFOA, and PFOS with low vapor pressure and high solubility tend to be the dominant species in airborne particulate matter.

The particle-associated phase can absorb to atmospheric particulate matter such as PM_{10} and $PM_{2.5}$, which results in long-range transport and deposition. The atmospheric half live of precursors such as FTOH of 20 days further facilitates in intercontinental transport [5]. There are documented evidence of PFAS transport from manufacturing regions in China and North America to remote regions such as the Arctic and Tibet, confirming long range atmospheric transport (LRAT).

The particle bound PFAS can settle onto land and water surfaces. In the areas downwind of emission sources, the PFAS can be removed from the air due to rain or snow thereby traveling with precipitation on land or water bodies. It can also bioaccumulate in plants and animals.

The atmospheric transformation includes oxidation of semi-volatile compounds such as FTOHs and FASAs, eventually transforming into terminal PFAS compounds like PFOA and PFOS. Table 1 summarizes the fate and transport of PFAS in the atmosphere.

Table 1. Summary of Fate and Transport of PFAS in Atmosphere.

Process	Description
Long-Range Transport	PFAS precursors can travel thousands of kilometers via global wind currents.
Photooxidation	FTOHs and FASAs degrade to stable acids such as PFOA or PFNA
Dry Deposition	Particle-bound PFAS settle onto land and water bodies.
Wet Deposition	Rain and snow scavenge PFAS from air, contributing to surface water loading.

The dynamics of atmospheric residence times varying from days to months, enabling regional and global dispersion necessitate effective airborne control strategies at the source and during waste processing.

4 Control Strategies

The control strategies for airborne PFAS emissions includes source control and treatment, identifying alternatives through green chemistry, and establishing a monitoring and risk assessment framework.

4.1 PFAS Air Pollution Control Technologies

4.1.1 Adsorption-Based Techniques

Adsorption based techniques are effective in control PFAS air pollution as volatile and semi-volatile PFAS compounds could be captured from industrial stacks, off-gases from remediation processes and ambient air stream in some cases. This option is comparatively less energy intensive as compared to thermal destruction and a potential for modular deployment in both fixed and mobile applications. The process of adsorption involves passing PFAS molecules over high surface area carbon structures. Granular Activated Carbon (GAC) or Powdered Activated Carbon (PAC) used in the adsorption process is often derived from coconut shell, wood or coal. Given the modular nature of these systems, this technique is usually applied to industrial stacks, air filtration systems and emergency vapor capture systems in PFAS remediation. The key performance factor in adsorption is the PFAS chain length, the longer chain adsorbs more readily as compared to shorter chain molecules. Humidity and co-contaminants can also impact the adsorption rates. In addition, the adsorbing media requires proper treatment such as thermal or solvent regeneration prior to end of disposal.

4.1.2 High-Temperature Thermal Oxidation (HTTO)

This technique is used to eliminate PFAS from gas streams. The destruction method involves combustion of PFAS gas stream in a refractory-lined combustion chambers at temperatures above 1100°C [6]. The high combustion temperature is required to break the C-F bonds. Table 2 describes the operating parameters of HTTO process. The following is a general equation that describes the reaction chemistry of HTTO:

$$C_7F_{15}COOH + O_2 \rightarrow 7\ CO_2 + 15\ HF + H_2O \qquad (1)$$

Table 2. Operating Parameters of HTTO.

Parameter	Range	Description
Combustion temperature	>1,100°C (2,012°F)	Required to achieve >99% destruction of stable PFAS
Residence time	~2 seconds	Allows for complete oxidation of fluorinated compounds
Oxygen concentration	6–10% excess O_2	Supports complete combustion; prevents dioxin/CO formation
Quenching system	Rapid post-combustion cooling	Prevents recombination of intermediates
Scrubbing system	Caustic wet scrubber	Captures HF, COF_2, and other acidic byproducts

The destruction efficiency of HTTO has been demonstrated to be greater than 99.99%. Given optimum residence time control and scrubbers post combustion chamber, PFAS could be destroyed with minimal toxic byproduct formation. However, there are some design and operational challenges that are faced by the HTTO space. Some of the waste gases such as HF are highly acidic and requires appropriate material of construction. There could be generation of toxic byproducts if the residence time is inadequate, combustion temperatures are lower and if there is a lack of scrubbing operation post combustion. Waste heat recovery systems could be implemented to leverage the high energy intensity nature of this process. Other strategies to overcome some of the design and operational challenges include:

1. Incorporating pre-treatment such as filtration or gas cooling to address high particulate loading
2. Reaction kinetics could be better controlled if direct or indirect cooling or quenching mechanisms are installed.
3. Ensure scrubbing process and equipment are in working condition to tackle gases such as HF, SO2 and COF2.

4.1.3 Non-Thermal Plasma Reactors

This technology involves high-voltage electrical discharge to generate reactive species such as electrons, ions and radicals. The electrically charged ions and electrons initiate the chemical reaction that can lead to degradation of the PFAS into smaller compounds such as CO2, HF and other short-chain fluorinated species. The destruction efficiency of this technology can range between 60-95% depending upon the target pollutant and reactor design. The energy yield is around 10-100 g PFAS/kWh and the operating temperature is usually below 200 ˚C. The lower operating temperature is one of the advantages of this technology. Other advantages include avoidance of thermal byproducts such as dioxins and furans. This technology also uses comparatively lower energy as compared to HTTO. The typical residence time ranges between milliseconds to seconds. However, there are certain challenges to this technology including incomplete destruction, scale-up complexity and equipment fouling.

4.1.4 Advanced Oxidation Technologies (AOTs)

Similar to non-thermal plasma technology, the AOT utilizes reactive species, mainly hydroxyl radicals (•OH) and superoxide (O_2^-) to initiate non-selective oxidation of volatile and semi-volatile PFAS. Semiconductor materials such as titanium dioxide, zinc oxide laced with WO3 is activated by UV light to generate electron-hole pairs that create oxidative radicals. A sample reaction is described as follows:

$$\mathrm{ZnO} + h\nu \rightarrow e^- + h+ \tag{2}$$

$$h+ + \mathrm{H2O} \rightarrow \bullet\mathrm{OH} \tag{3}$$

$$e^- + \mathrm{O2} \rightarrow \mathrm{O_2^-}\bullet \tag{4}$$

These species react with PFAS molecules via decarboxylation or defluorination and oxidation of precursors to terminal acids. The destruction efficiency can range between 60-95% for PFOS, PFOA and FTOHs. However, the efficiency is limited for stable acids like PFOS and PFOA due to strong C-F bongs. The efficiencies are improved by adding oxidants along with the UV. This technology has the advantage of operating in mild conditions with minimal thermal footprint. The operating temperature can range from ambient to 120 C. The residence time can range from 0.5 – 3 seconds.

Some of the challenges in this technology include incomplete degradation of stable PFAS. Terminal acids such as PFOA requires enhanced UV power. Photocatalyst fouling can occur with humid or particulate loading which requires pre-filtration. For high-flow systems, light penetration limitation could affect photocatalysis. The short chain PFAS molecules are more mobile, hence they are less reactive under the photocatalysis conditions. However, with doping and integrating with non-thermal plasma or catalytic oxidation, these challenges could be addressed. Table 3 summarizes the above discussed air pollution control technologies for PFAS.

Table 3. Summary of Air Pollution Control Technologies for PFAS.

Technology	Principle	PFAS Removal Efficiency	Consideration
Activated Carbon Adsorption	Physical adsorption	Moderate to High	Depends on PFAS volatility
Ion Exchange Resins	Electrostatic interaction	Moderate	Limited field data
High-Temp Thermal Oxidation	Combustion >1100°C	High (>99%)	Requires scrubber to remove byproducts
Non-Thermal Plasma Reactors	Reactive species formation	Moderate (Pilot-stage)	Under active research
UV-Photocatalysis	Oxidative degradation	Low to Moderate	Effective on PFAS precursors

4.2 Emerging Solutions

As evident from the previous section, the airborne emissions of PFAS are complex to treat and require novel approach. With the intensification of regulatory scrutiny along with new discoveries about the impact from airborne PFAS, emerging technologies are being developed to address this complex challenge. Some of these innovations are further development and efficiency enhancement of non-thermal plasma reactors, catalytic filtration, advanced adsorption and data-driven process optimization. These technologies offer promising pathways to reduce PFAS air emissions and mitigate their environmental and health impacts.

4.2.1 Catalytic Filtration Systems

This emerging air pollution control technology is designed to degrade volatile and semi-volatile PFAS compounds in gaseous streams. The treatment system includes a ceramic or metallic substrate coated with noble or rare earth metal catalysts such as cerium, platinum, or manganese oxides. This system requires operation at moderate to high temperatures (typically 300–700°C). The PFAS-contaminated air passes through the catalytic bed thereby initiating the oxidation reactions that break the strong C–F bonds. As a typical goal of this technology is to convert harmful fluorinated organics into non-toxic byproducts such as CO_2, HF, and H_2O. Unlike traditional thermal incineration, catalytic systems are less energy intensive, produce fewer toxic byproducts, and demonstrate greater operational stability, specifically when integrated with scrubbers to capture acidic gases. Pilot studies have demonstrated destruction efficiencies exceeding 90% for PFAS making catalytic filtration a promising tool for industrial facilities seeking to reduce airborne PFAS emissions.

However, the catalyst deactivation can place due to fouling or fluorine accumulation. The technology requires optimization of residence time and temperature control

4.2.2 Biochar and Functionalized Sorbents

This passive capture technology is generating interest due to lower cost intensity in the removal of volatile and semi-volatile PFAS species from the atmosphere. The biochar is derived from the pyrolysis of organic biomass, and it offers high surface area for the adsorption of PFAS precursors such as FTOHs and FASAs. Research has shown that biochar can be functionalized with amine groups, metal oxides or activated carbon coatings to improve their selectivity and affinity for a larger range of PFAS species [7]. This technology is currently under developmental stage for large-scale operations. The low energy requirements, renewable nature and onsite regeneration potential makes this a lucrative option.

One of the drawbacks of this technology is that it doesn’t result in complete destruction, rather the media must be either disposed or regenerated. In addition, the adsorption capacity and efficiency depends on the temperature and chain length of the PFAS

4.2.3 Supercritical Water Oxidation (SCWO)

This is an emerging high-efficiency destruction technology designed to convert PFAS compounds into benign end-products under extreme reaction conditions. The process involves passing contaminated gases through an aqueous phase followed by exposure to supercritical water, with temperatures above 374°C and a pressure of 22.1 MPa, in the presence of an oxidant such as oxygen or hydrogen peroxide [8]. These conditions render the organic compounds fully miscible in water, which facilitates in rapid and complete oxidation reactions. The contaminated vapor streams are usually pre-scrubbed or absorbed into water to facilitate feed into the SCWO reactor. Similar to the other destruction technologies, this process ensures the conversion of persistent fluorinated compounds into CO_2, HF, and H_2O. The bench scale setups have demonstrated destruction efficiencies exceeding 99.99%. SCWO is particularly attractive for treating concentrated off-gas, such as from AFFF destruction or fluorochemical manufacturing, due to its minimal byproduct formation and ability to handle mixed waste streams.

While system complexity, high capital and operational cost, inlet gas pre-treatment requirement and material corrosion remain engineering challenges, SCWO represents a near-zero emissions solution for the complete destruction of PFAS captured from air.

4.2.4 AI-Enhanced Predictive Emission Modeling

The use of artificial intelligence (AI) and machine learning (ML) are increasingly being integrated into predictive emission modeling frameworks to improve the detection, quantification, and management of airborne PFAS. While these tools are not treatment technology, they leverage large datasets—ranging from process conditions, meteorological parameters, and historical emission profiles—to forecast PFAS dispersion patterns, transformation pathways, and potential human or ecological exposure zones. AI models can dynamically simulate the behavior of volatile precursors like FTOHs and FASAs, accounting for their chemical degradation, partitioning, and long-range atmospheric transport. AI models are also being trained on real-time sensor data from facility stacks, ambient air monitors, and meteorological feeds to generate proactive alerts when emission trends deviate from expected baselines. In industrial settings, AI-enhanced systems can guide adaptive process control, optimize scrubbing or capture efficiency, and support regulatory reporting with more precise and validated predictions. By enabling data-driven risk forecasting and emission reduction planning, AI-powered modeling represents a transformative tool in managing the complex and diffuse nature of airborne PFAS pollution [9]. However, this is dependent on high-quality input data and model validation. Table 4 summarizes the emerging PFAS treatment technologies.

Table 4. Summary of Emerging PFAS Treatment Techniques.

Technology	Primary Mechanism	Destruction/Removal Efficiency	Status
Catalytic Filtration	Surface-catalyzed PFAS decomposition	Moderate to High (~80–90%)	Pilot-stage
Biochar & Functional Sorbents	Adsorption via surface functional groups	Moderate (depends on PFAS type)	Field-tested
Supercritical Water Oxidation	Oxidation under high temp/pressure	Very High (>99.99%)	Full-scale trials
AI-Enhanced Emission Modeling	Predictive analytics & dispersion tracking	Indirect – prevention focused	Operational pilots

5 Monitoring and Risk Management Framework

The pathway to develop an effective PFAS management framework includes prevention of uncontrolled PFAS releases to the atmosphere, detection and quantification of PFAS at source and in ambient atmosphere, respond with control technologies, evaluate long-term exposure and policy effectiveness and finally communicate the risks and outcomes to stakeholders. Figure 1 describes the PFAS air pollution control framework.

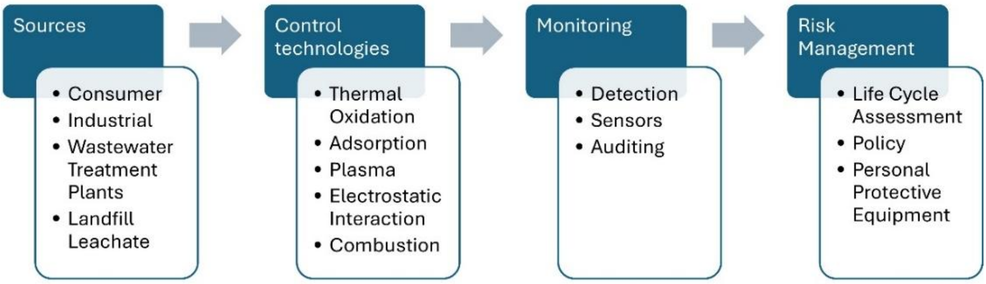

Fig. 1. PFAS Air Pollution Control Framework.

Within the monitoring phase, the detection and quantification of PFAS has been in an ever-evolving phase. The source monitoring framework involves identifying PFAS emissions using stack testing, leak detection, process reviews and inspections. The quantification can be done either using existing methods such as EPA Method OTM-50, TO-134 or TOF-MS, or by engineering estimates. Integrating PFAS sampling with existing sampling ports and real-time gas sensors for PFAS precursors such as FTOHs and PFOS would enhance the quantification. Apart from source monitoring, ambient monitoring using fixed air samplers, passive samplers, mobile monitoring units and real-time analytics assists in further quantification.

The risk management aspect includes managing existing PFAS risks through policy, personal protective equipment and life cycle assessment (LCA). Air filtration systems and personal protective equipment reduce exposure risks in workplaces handling PFAS. Zone monitoring in high-risk areas such as coating lines and thermal treatment zones will further enhance the monitoring network. The LCA evaluations of PFAS assess the total environmental burden across air, water, soil and human health. It also presents the trade-offs in production vs substitution vs treatment. A multi-media LCA model is much more beneficial than a specific media which can result in better informed decision making.

Given the fact that airborne PFAS control is still at its infancy stages, there are several barriers that continue to limit the widespread application and reliability of PFAS air control technologies. These challenges are summarized in the Figure 2.

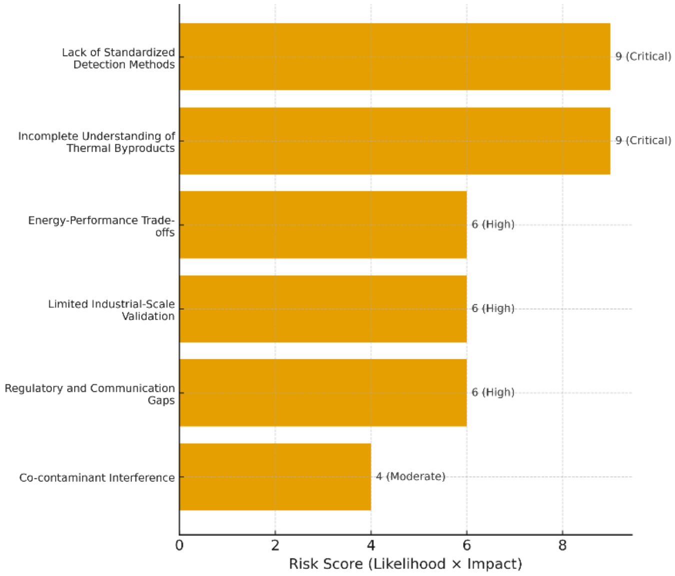

Fig. 2. Risk Ranking of PFAS Air Emission Control Challenges.

6 Conclusion

The PFAS related air pollution control is fairly complex and requires a cross-disciplinary and coordinated approach. The range of PFAS species, their chemical and physical behavior in different atmospheric conditions and persistence involves strategic approaches. Some of these approaches include source reduction and preventative strategies such as green chemistry innovations, phasing out the volatile PFAS compounds from industrial processes, coatings, and surfactants. Advanced solutions such as catalytic filtration, supercritical water oxidation (SCWO), and engineered adsorbents show considerable promise but require further optimization, cost reduction, and demonstration at scale. Deploying sensor-based monitoring tools and fluorine-specific analyzers is essential for identifying and responding to emissions quickly. Investment in standardized air sampling protocols and detection methods is a key enabler. Regulatory frameworks also need to be updated to address airborne PFAS directly. Clear guidance on allowable limits, best available technologies (BAT), and emission thresholds will accelerate technology adoption.

Furthermore, insights from AI-enhanced modelling, techno-economic assessments, and life cycle analyses should inform not only the selection of control technologies but also long-term planning for facility design, emissions compliance, and public health protection. Continued investment in basic and applied research, especially on PFAS transformation chemistry, health risk assessments, public awareness and atmospheric fate, will be essential to closing current knowledge gaps.

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