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Per-and polyfluoroalkyl substances (PFAS) in the environment (Water, soil & food) an integrated review: History, sources, surveys, health effects, extraction, analysis, and remediation

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Abstract
Per- and polyfluoroalkyl substances (PFAS), often termed "forever chemicals," represent a formidable class of synthetic contaminants characterized by their extreme environmental persistence, conferred by the robust carbon-fluorine bond. This review provides a holistic synthesis of the complete lifecycle of PFAS, tracing their trajectory from mid-20th-century industrial development to their current status as a global environmental and public health dilemma. It delineates their diverse sources from industrial discharges and aqueous film-forming foams (AFFF) to landfill leachates and consumer products, which facilitate their widespread dissemination into water, soil, and the food chain. The paper consolidates findings from global environmental surveys, confirming the ubiquitous presence of both legacy compounds and emerging alternatives in ecosystems worldwide, supported by a localized case study from the Saudi Arabian Red Sea. A critical examination of the substantial body of evidence links PFAS exposure to significant adverse health outcomes in humans, including immunotoxicity, endocrine disruption, metabolic dysregulation, and developmental neurotoxicity. The review further details the sophisticated methodologies essential for their extraction and analysis from complex matrices, underscoring the central role of liquid chromatography-tandem mass spectrometry (LC-MS/MS) and high-resolution techniques. Finally, it provides a critical assessment of the remediation landscape, contrasting established adsorption methods with innovative destructive technologies such as advanced oxidation/reduction processes, sonolysis, and electrochemical techniques. The synthesis concludes that mitigating the PFAS challenge necessitates an integrated, multifaceted strategy, combining robust regulatory frameworks that address PFAS as a class, continuous environmental monitoring, and the advancement of scalable, destructive treatment solutions to permanently eliminate these persistent pollutants.

Keywords: PFAS, forever chemicals, environmental persistence, health risk assessment, pollution control, advanced water treatment, contaminant degradation.

Introduction

Per- and polyfluoroalkyl substances (PFAS) represent a vast and complex family of synthetic chemicals, defined by their unique molecular architecture where hydrogen atoms in an alkyl chain are extensively or fully substituted by fluorine atoms [1-3]. This fundamental structure gives rise to the exceptionally strong carbon-fluorine (C–F) bond, one of the most durable in organic chemistry, which underpins the remarkable thermal, chemical, and biological stability of these compounds [4]. Furthermore, the amphipathic nature of PFAS, featuring a hydrophobic fluorinated tail paired with a hydrophilic, often charged, head group, is the foundation of their superior surfactant qualities [5].

These very properties-profound stabilities and surface-active capability-propelled their widespread integration into a multitude of industrial and consumer applications from the mid-20th century onward. PFAS became critical components in products ranging from non-stick cookware and water-repellent fabrics to food packaging and highly effective aqueous film-forming foams (AFFF) used in firefighting [1, 6-8]. Paradoxically, the characteristics that made PFAS commercially indispensable are also the source of a profound environmental and public health crisis. Their celebrated stability translates into extreme persistence in the environment, earning them the moniker "forever chemicals" [5]. Their mobility and solubility allow them to bypass conventional wastewater treatment processes largely unscathed, facilitating their nearubiquitous dispersion into water, soil, and the food chain [6, 9-11]. The collective impact of manufacturing, use, and disposal has resulted in pervasive global contamination, with detections recorded even in pristine remote regions such as the Arctic [12]. Among the thousands of PFAS compounds identified, only a handful, including perfluorooctanoic acid (PFOA) and perfluoro octane sulfonate (PFOS), have been studied extensively, yet their frequent detection has spurred significant regulatory actions, such as their listing under the Stockholm Convention [13].

This widespread environmental presence establishes multiple pathways for human exposure, primarily through the consumption of contaminated drinking water and food, leading to the near-universal detection of PFAS in human serum [9, 14]. A substantial and growing body of toxicological and epidemiological evidence has linked PFAS exposure to a spectrum of adverse health outcomes, including immunotoxicity, endocrine disruption, and metabolic dysfunctions [14, 15]. This challenge is particularly pressing in water-scarce regions like Saudi Arabia, where safeguarding the integrity of water resources is paramount, underscoring the urgent need for vigilant management of these persistent pollutants [16].

Consequently, this review aims to deliver a comprehensive and integrated synthesis of the current knowledge on PFAS. It will trace their historical arc from industrial innovation to global contaminant, delineate their diverse sources and environmental pathways, and consolidate findings from worldwide surveillance studies. The paper will critically evaluate the evidence for health impacts, detail advanced methodologies for their extraction and analysis from complex matrices, and assess the evolving landscape of remediation technologies. By weaving together this multidisciplinary knowledge, this review seeks to inform future research directions, bolster the development of robust regulatory frameworks, and contribute to crafting effective strategies to mitigate the impact of these enduring chemicals on both ecosystems and public health.

History

The historical trajectory of per- and polyfluoroalkyl substances (PFAS) began in the 1940s, with their initial development linked to the Manhattan Project, where their unique properties were utilized in uranium enrichment processes [5, 8]. Following this specialized application, the commercial and industrial use of PFAS expanded rapidly from the mid-20th century onward, capitalizing on their exceptional stability and surfactant characteristics [1, 3]. This led to their incorporation into a vast array of consumer and industrial products, including non-stick cookware, water-resistant textiles, and highly effective aqueous film-forming foams (AFFF) for firefighting [1, 6, 7]. For decades, these substances were manufactured and deployed with a limited understanding of their long-term environmental fate.

The first significant indicators of their environmental impact emerged with the detection of specific compounds like perfluoro octane sulfonic acid (PFOS) in wildlife, signaling their bioaccumulative potential and long-range transport long before they became a central focus of regulatory scrutiny [17, 18]. The scale of production was historically immense, with estimates suggesting that over 3,000 different PFAS have been placed on the global market, leading to their pervasive presence in consumer goods and the environment [19, 20].

By the early 21st century, accumulating scientific evidence on the extreme persistence, bioaccumulation, and toxicity of long-chain PFAS, particularly PFOA and PFOS, prompted significant regulatory action. This culminated in voluntary industry phase-outs in many regions and their eventual classification as persistent organic pollutants (POPs) under the Stockholm Convention [2, 15]. However, this regulatory focus on individual long-chain compounds led to a strategic industry shift towards the development and deployment of alternative substances, often shorter-chain PFAS (e.g., perfluorobutane sulfonate - PFBS) or compounds with ether linkages (e.g., GenX) [2, 3, 21]. This transition, unfortunately, has not resolved the core issue, as many of these alternatives also demonstrate environmental persistence and present their own challenges for remediation, with emerging evidence highlighting significant knowledge gaps regarding their full toxicological profile and bioaccumulative potential [21, 22].

The escalating concern is reflected in the scientific community's response; bibliometric data show a dramatic surge in research publications focused on PFAS, underscoring a global effort to understand and mitigate their impacts [20, 23]. Despite these efforts, the environmental legacy of long-chain PFAS endures, and the ongoing use of their replacements ensures that PFAS remain a permanent and evolving challenge for environmental management [2] [3]. Their detection in remote environments, such as the Arctic and high-altitude glaciers, stands as a testament to their pervasive and lasting impact [6, 24].

Sources

PFAS contamination originates from a complex interplay of point and non-point sources, facilitating their widespread environmental distribution. Direct industrial discharges from manufacturing facilities and the historical use of AFFF at military bases, airports, and fire-training grounds are significant point sources, often leading to severe local groundwater and soil contamination [1, 6, 7]. Specific industrial sectors, including textile manufacturing, chemical production, tanneries, and paper processing, are notable contributors. Industrial effluents, particularly from hubs in regions like Gujarat, Maharashtra, and Tamil Nadu in India, have been documented to contain elevated concentrations of PFOS, PFOA, and precursors such as 6:2 fluorotelomer sulfonate (6:2 FTSA) [25].

Landfills receiving PFAS-containing consumer products act as concentrated secondary sources, where leachate can transport these compounds into adjacent environments [6, 26]. Wastewater treatment plants (WWTPs) represent another critical pathway; conventional treatment processes are largely ineffective at destroying PFAS, leading to their discharge into rivers and lakes from urban centers worldwide, including major cities like Delhi, Mumbai, and Chennai [27, 28]. A case study from Saudi Arabia further illustrates this, where treated and untreated sewage effluents from WWTPs have been identified as major contributors to PFAS levels in the coastal waters of the Red Sea [41].

Non-point sources are more diffuse and include atmospheric deposition of volatile precursors, surface runoff from treated urban areas, and the application of PFAS-laden biosolids and reclaimed water in agriculture [9, 10]. This agricultural practice facilitates the uptake of PFAS by crops, introducing them directly into the human food chain [9, 10]. The use of contaminated water for irrigation further exacerbates this pathway [10]. The ubiquity of PFAS in everyday items—from food packaging, cosmetics, and stain-resistant fabrics to consumer goods ensures a continuous and widespread release into the environment post-disposal or during use, making containment and management exceptionally challenging [1, 3, 29]. Furthermore, the incineration of waste containing PFAS can lead to their release into the atmosphere [30]. The distinct PFAS signature (often dominated by PFHxA, PFHxS, and 6:2 FTS) found in environments near firefighting stations, consistent with AFFF-impacted sites globally, underscores the persistent nature of this source [31].

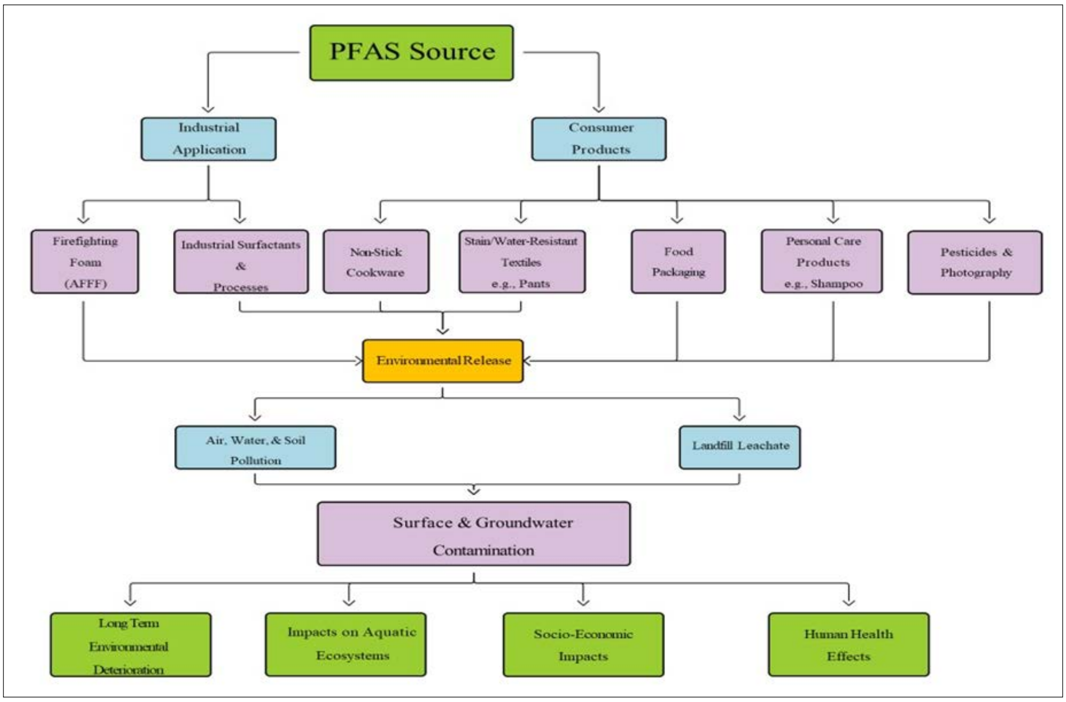

Fig 1: Primary sources of PFAS and their subsequent impact on environmental matrices and human health [32, 34]

The diagram illustrates the common industrial and consumer products that release PFAS into the environment, ultimately leading. The contamination of soil and water, and posing a risk to human health. Adapted from information in the provided documents.

Table 1: Classification and Examples of Major Per- and Polyfluoroalkyl Substances (PFAS). [32, 35]

PFAS Category	Specific Compound	Abbreviation	General Formula / Chemical Structure
Perfluoroalkyl Acids (PFAAs)	Perfluorooctanoic acid	PFOA	$C_7F_{15}COOH$
	Perfluoroalkane sulfonates	PFSAs	$C_nF_{2n+1}SO_3H$ (e.g., PFOS: $C_8F_{17}SO_3H$)
Perfluoroalkane Sulfonamides	N-Methyl perfluorooctane sulfonamide	MeFOSA	$C_8F_{17}SO_2NH(CH_3)$
	N-Alkyl perfluoroalkane sulfonamides	FASAs	$C_nF_{2n+1}SO_2NHR$ ($R = C_mH_{2m+1}$, m=1,2,4)
Sulfonamido-based Derivatives	N-Methyl perfluorooctane sulfonamidoethanol	FOSE	$C_8F_{17}SO_2N(CH_3)CH_2CH_2OH$
	Perfluoroalkane sulfonamido-acetic acids	FASAAs	$C_nF_{2n+1}SO_2N(R)CH_2COOH$ ($R= C_mH_{2m+1}$, m=0,1,2,4)
Fluorotelomers	n:2 Fluorotelomer alcohols	n:2 FTOHs	$C_nF_{2n+1}CH_2CH_2OH$ (e.g., 10:2 FTOH: $C_{10}F_{21}CH_2CH_2OH$)
	n:2 Fluorotelomer sulfonic acids	n:2 FTSAs	$C_nF_{2n+1}CH_2CH_2SO_3H$ (e.g., 8:2 FTSA: $C_8F_{17}CH_2CH_2SO_3H$)
	n:2 Fluorotelomer carboxylic acids	n:2 FTCAs	$C_nF_{2n+1}CH_2COOH$ (e.g., 8:2 FTCA: $C_8F_{17}CH_2COOH$)
	7:3 Fluorotelomer carboxylic acid	7:3 Acid	$C_7F_{15}CH_2CH_2COOH$

* n number of carbons in chain, m number of alkyl groups

Surveys

Environmental monitoring studies have unequivocally demonstrated the global dissemination of PFAS. They are routinely detected in rivers, lakes, oceans, and groundwater reservoirs across all inhabited continents, confirming their ubiquitous nature [6, 27]. Their pervasive distribution extends even to remote and minimally inhabited regions, such as the Arctic, where PFAS have been identified in the blood of polar bears and other wildlife, underscoring their long-range transport potential [36].

Human biomonitoring confirms nearly universal serum presence of PFAS in the general population, with elevated concentrations consistently observed in communities residing near identified point sources, such as industrial facilities or fire-training areas [15, 27]. Diet, particularly the consumption of contaminated water, seafood, and agricultural products, remains a major exposure route for the broader population [9, 10]. Specific regional surveys provide critical insights into localized contamination patterns. In India, studies have documented PFAS in various environmental matrices, with PFOS and PFOA concentrations in Chennai's surface waters ranging from 3 to 93 ng/L, linked to industrial and urban wastewater discharges [37]. Groundwater resources in the same region have shown concentrations as high as 136 ng/L, posing a direct threat to drinking water supplies [38]. Bioaccumulation within the food web is evidenced by the detection of PFAS in aquatic species, such as fish and dolphins from the Ganges River, and human exposure is further confirmed by their presence in serum and breast milk samples from populations in Chennai and Kolkata [39, 40].

Similarly, a pivotal baseline survey in the Saudi Arabian Red Sea provided the first quantitative data for this ecosystem, revealing the sum of 12 target PFAS (Σ_{12} PFAS) in surface seawater ranging from below the limit of quantification to 956 ng/L [41]. The highest concentrations were identified in semi-enclosed lagoons receiving continuous sewage discharge, starkly contrasting with a nearby reference site, which recorded significantly lower levels. This pattern vividly illustrates the profound impact of localized anthropogenic sources and highlights the utility of such studies in identifying contamination hotspots [41].

In response to the pervasive detection of PFAS and growing understanding of their toxicity at low concentrations, regulatory agencies worldwide have established increasingly stringent health advisories and legally enforceable limits for drinking water. For instance, the United States Environmental Protection Agency (USEPA) has set maximum contaminant levels at 4.0 parts per trillion (ng/L) for PFOA and PFOS, and 10 ppt for PFNA, PFHxS, and HFPO-DA (GenX) [42]. China has implemented standards of 80 ng/L for PFOA and 40 ng/L for PFOS [43]. The extremely low levels of these standards reflect the compounds' potent toxicity and pose a significant challenge for both quantitative analytical detection and effective water treatment. This regulatory landscape has prompted some nations to consider regulating total organofluorine as a class, thereby making the complete degradation of PFAS a paramount treatment objective [44].

Evaluations of drinking water sources, especially near industrial sites or areas with historical AFFF usage, frequently reveal PFAS concentrations that exceed these stringent health guidelines [6, 45]. Predictive modeling for regions with expanding industrial bases, such as India, forecasts a sharp increase in surface water PFAS concentrations over the coming decades, with levels in some states anticipated to exceed international safety thresholds by more than tenfold, highlighting a critical future public health risk [46]. These comprehensive surveys and predictive models are indispensable for mapping exposure hotspots, understanding environmental transport mechanisms, and informing the development of proactive public health policies and remediation priorities.

Table 2: Environmental Pathways and Compartments of Chemical Pollutants [47]

Source / Emission	Transfer Pathway / Process	Receiving Environmental Compartment	Potential Impact / Endpoint
Air Emission	Volatilization (to Gas Phase)	Atmosphere	Long-range atmospheric transport and deposition.
	Particulate Transport & Dry/Wet Deposition	Terrestrial Ecosystems, Surface Water	Contamination of soil and water bodies via fallout.
	Run-off	Surface Water	Transport of deposited pollutants to aquatic systems.
Anthropogenic Source	Water Emission / Effluent Discharge	Surface Water, Groundwater	Direct introduction of contaminants into aquatic environments.
	Wastewater Treatment & Sludge Production	Landfill, Agricultural Soil	Transfer of contaminants to solid waste or soil via sludge application.
	Waste Disposal (Landfill)	Soil, Groundwater	Leaching of contaminants from disposal sites.
Soil Compartments	Leaching	Groundwater	Infiltration of contaminants into underground water resources.
	Uptake & Bioaccumulation	Terrestrial Ecosystems	Entry of contaminants into the food web.
Aquatic Compartments	Effluent Dilution & Transport	Freshwater, Marine Water	Dispersion and dilution of pollutants in water bodies.
	Uptake & Bioaccumulation	Aquatic Ecosystems	Entry and magnification of contaminants in the aquatic food web.
Ecosystems & Humans	Food Web Transfer & Exposure	Humans	Human exposure occurs through the consumption of contaminated water and food.

Health Effects

Epidemiological and toxicological research has linked PFAS exposure to a spectrum of adverse health outcomes, raising significant public health concerns for both humans and wildlife [14, 15]. The risk associated with these compounds is magnified by their ability to bioaccumulate in tissues and resist metabolic degradation, leading to prolonged internal exposure, even at low concentrations that are now normative for most populations [9, 14].

A substantial body of evidence confirms that the immune system is a particularly sensitive target for PFAS. Exposure has been consistently correlated with immunotoxicity, most notably a reduced antibody response to vaccines in children, suggesting a weakened defense against infectious diseases at a population level [14, 42, 48]. Endocrine and metabolic disruptions are also well-documented. PFAS exposure interferes with thyroid hormone regulation, potentially leading to thyroid disease [49], and is associated with dyslipidemia, including elevated cholesterol levels [50].

1. Hepatotoxicity and Metabolic Dysfunction

Beyond dyslipidemia, PFAS are recognized as potent metabolic disruptors that directly impact liver function. Recent longitudinal studies have established a strong association between PFAS exposure and the development of non-alcoholic fatty liver disease (NAFLD). The proposed mechanisms include the strong affinity of many PFAS for liver tissue, where they can activate the peroxisome proliferator-activated receptor (PPARα) and constitutive androstane receptor (CAR), leading to alterations in lipid metabolism, mitochondrial dysfunction, and increased oxidative stress within hepatocytes. This can progress to steatosis (fatty liver) and, in more severe cases, non-alcoholic steatohepatitis (NASH), highlighting the liver as a key target organ for PFAS toxicity [51, 52].

2. Carcinogenic Potential

The carcinogenic potential of certain PFAS is a major area of concern. Epidemiological studies have established associations between exposure to legacy compounds like PFOA and PFOS and an increased risk of specific cancers, particularly of the kidneys and testes [53]. Evidence is also mounting for a potential link to liver and pancreatic cancers, as sustained activation of nuclear receptors and chronic inflammation in these organs may create a pro-carcinogenic microenvironment [54].

3. Reproductive, Developmental, and Neurotoxic Effects

Reproductive and developmental toxicity represents another critical endpoint. Prenatal exposure is linked to complications such as preeclampsia and can lead to adverse birth outcomes, including low birth weight and developmental alterations, effects partly mediated through placental transfer [14, 55].

3.1 Neurodevelopmental Toxicity

A growing body of evidence from both epidemiological cohorts and animal models suggests that early-life PFAS exposure can have significant neurodevelopmental consequences. Studies report associations with decreased IQ, increased attention-deficit/hyperactivity disorder (ADHD) symptoms, and impaired cognitive function in children. Proposed mechanisms include the disruption of thyroid hormone homeostasis (critical for brain development), induction of neuroinflammation, and direct interference with neuronal differentiation and synaptic function. The developing brain appears uniquely vulnerable, underscoring the critical nature of the exposure window [56-58].

4. Emerging Health Endpoints: The Gut Microbiome

One of the most novel frontiers in PFAS toxicology is its impact on the gut microbiome. Preliminary in vivo and in vitro studies indicate that PFAS exposure can induce gut microbiota dysbiosis, characterized by a reduction in beneficial microbial species and an increase in pathogenic ones. This disruption can compromise gut barrier integrity, potentially leading to a "leaky gut" and systemic inflammation. Furthermore, PFAS-induced changes in microbial metabolism may influence host health, including energy harvest and immune function, suggesting a plausible pathway for some of the metabolic and immunological effects associated with these compounds [59-61].

5. Mechanistic Underpinnings of Toxicity

The mechanistic underpinnings of these diverse health effects are actively being unraveled. Toxicological studies reveal that PFAS can induce oxidative stress, cause mitochondrial dysfunction, and act as potent endocrine disruptors. They achieve this by interfering with key cellular receptors, such as the peroxisome proliferator-activated receptors (PPARs) and estrogen receptors, thereby disrupting fundamental hormonal and metabolic pathways [5, 62]. Notably, some emerging PFAS alternatives have been shown through *in silico* and *in vitro* models to exhibit even more potent disruptive effects, such as anti-androgenic activity, than their legacy predecessors [63].

6. Ecological Impacts

Ecological impacts parallel these human health concerns. PFAS contamination has been demonstrated to cause reduced growth in plants, reproductive toxicity in fish, and bioaccumulation throughout aquatic food webs, thereby posing a threat to ecosystem integrity and function [63, 64]. The detection of PFAS in marine organisms, such as those from the Red Sea, confirms the existence of this exposure pathway and highlights a potential health risk for communities reliant on seafood [65]. Recent studies have documented sub-lethal effects in wildlife, including altered feather development in birds, immunosuppression in marine mammals, and impaired reproduction in amphibians, all of which can have cascading effects on population dynamics and biodiversity [66, 67].

While the understanding of legacy PFAS like PFOA and PFOS is growing, the toxicological profiles and health implications of many emerging alternatives remain inadequately characterized, representing a critical data gap that necessitates urgent research attention [68].

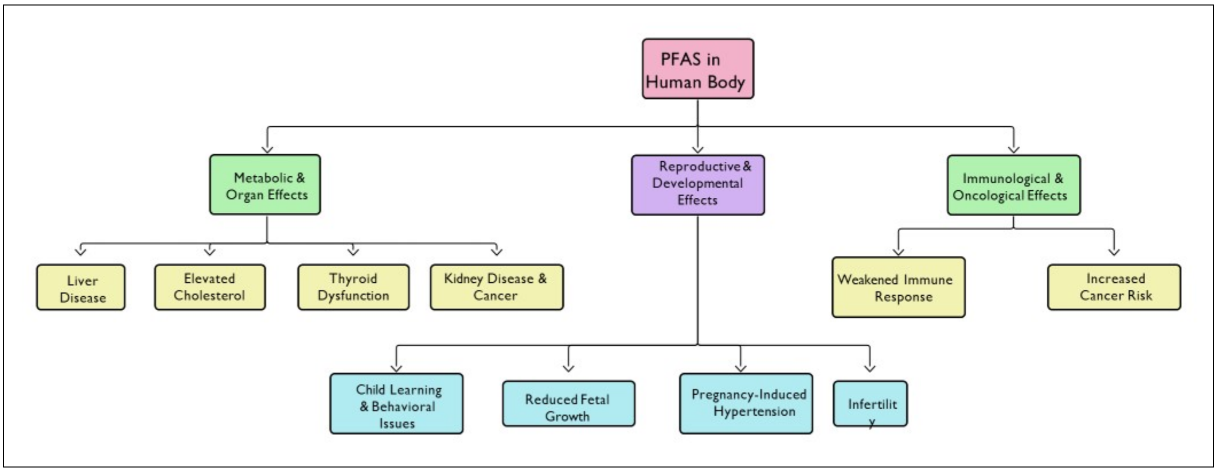

Fig 2: Exposure pathways and health effects of PFAS on human life [34, 35]

Extraction and Analysis

The accurate quantification of per- and polyfluoroalkyl substances (PFAS) in complex environmental and biological matrices is a cornerstone of understanding their distribution, exposure risks, and the efficacy of remediation strategies. This process demands a rigorous, twostage analytical approach: efficient extraction to isolate the analytes from complex samples.

Followed by highly sensitive and selective instrumental analysis to achieve the requisite detection limits, often at parts-per-trillion (ppt) levels [69, 70].

1. Extraction Techniques

The selection of an appropriate extraction method is paramount and is dictated by the physical state and composition of the sample matrix. The primary goal is to achieve high recovery of the target PFAS while minimizing co-extraction of interfering substances.

1.1 Aqueous Matrices

For water samples—including wastewater, surface water, and drinking water. Solid-Phase Extraction (SPE) is the established and most widely employed pre-concentration technique [69]. The choice of sorbent is critical for optimal performance. Hydrophilic-lipophilic balanced (HLB) polymers provide broad-spectrum retention, while anion-exchange sorbents offer greater selectivity. Specifically, weak anion exchange (WAX) sorbents are effective for capturing a wide range of anionic PFAS and their precursors, whereas strong anion exchange (SAX) resins excel in complex matrices like contaminated drinking water due to their superior selectivity [71]. Practical adaptations are often necessary for challenging samples; for instance, analyses of high-salinity seawater from the Red Sea have successfully utilized Oasis HLB cartridges to mitigate matrix-induced signal suppression during subsequent analysis [72, 73].

1.2 Solid Matrices

For solid samples such as soil, sediment, sludge, and biota, solvent-based extraction techniques are standard. Solid-Liquid Extraction (SLE)**,** where samples are homogenized with organic solvents like methanol, is commonly used to desorb and dissolve PFAS [69]. Methodologies such as QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) are increasingly favored for these complex matrices due to their effectiveness in both extraction and clean-up [71]. For the handling of concentrated wastes, advanced methods like liquid-liquid extraction assisted by ionic liquids are being explored for their potential to enhance extraction efficiency [74].

1.3 Quality Assurance in Extraction

A fundamental practice to ensure quantitative accuracy across all extraction methods is the use of isotope-labeled internal standards**.** These are added to the sample before the extraction process to correct for matrix effects, procedural losses, and instrumental variability, thereby guaranteeing the reliability and precision of the final data [70].

2. Analytical Techniques

Following extraction, the separation, identification, and quantification of PFAS rely on sophisticated instrumental platforms capable of achieving the necessary specificity and sensitivity.

2.1 Targeted Analysis: LC-MS/MS

Liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) is unequivocally the gold standard for the sensitive and selective quantification of a broad spectrum of targeted PFAS [69, 75]. The analysis typically employs reverse-phase chromatography (e.g., C18 columns) to separate different PFAS homologues. The mass spectrometer, often equipped with an electrospray ionization (ESI) source operating in negative ion mode, is set to Multiple Reaction Monitoring (MRM) mode. This technique enhances specificity by monitoring unique precursor-to-product ion transitions for each target compound, enabling reliable quantification at ultra-trace levels (ng/L or pg/L) in diverse samples, from drinking water to human serum [72]. Implementing rigorous quality control measures, such as using delay columns to trap background PFAS from the LC system and analyzing procedural blanks, is essential to prevent contamination and ensure data integrity [72].

2.2 Non-Targeted and Suspect Screening

For the identification of unknown and emerging PFAS not covered by standard analytical panels**,** non-targeted analysis (NTA) and suspect screening using high-resolution mass spectrometry (HRMS) are indispensable [75, 76]. These powerful approaches, supported by sophisticated data mining software and predictive models, allow for a more comprehensive assessment of the PFAS burden in environmental samples, as demonstrated in studies conducted near fluorochemical manufacturing plants [74].

2.3 Complementary Bulk Parameter Methods

Given the limitations of targeted methods, which are confined to available analytical standards, complementary techniques are vital for a complete contamination profile. Methods that measure Total Oxidizable Precursors (TOP Assay) **or** Total Organic Fluorine (TOF**)** are increasingly used to estimate the presence of PFAS not captured by targeted analysis. These bulk parameter methods provide a more holistic understanding of contamination levels and are crucial for validating the efficacy of remediation efforts that aim for complete defluorination [68]. This multi-faceted analytical framework, encompassing both targeted and non-targeted strategies alongside bulk parameter measurements, is therefore critical for accurate exposure assessment, regulatory compliance monitoring, and the development and validation of destructive treatment technologies.

Remediation

The remediation of per- and polyfluoroalkyl substances (PFAS) presents a formidable challenge to environmental engineering and public health communities, primarily due to the exceptional stability of their carbon-fluorine (C–F) bonds, their diverse presence in complex environmental matrices, and their propensity to accumulate in the food chain. A comprehensive remediation strategy must therefore encompass not only destructive and separation technologies but also sophisticated analytical methods for monitoring environmental fate and human exposure. Furthermore, the efficacy of any remediation effort is preconditioned by a deep understanding of the fundamental interactions between PFAS and the environment, particularly soil constituents, which govern their fate, mobility, and treatability.

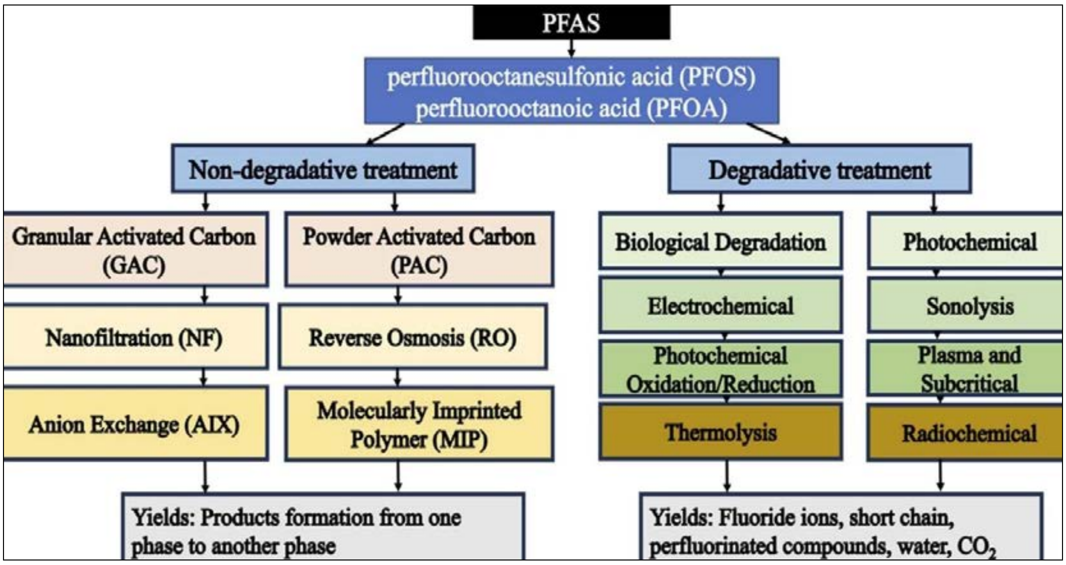

Fig 3: Degradative and non degradative treatment of PFAS [77]

1. The Critical Role of Advanced Analytical Methods in Guiding Remediation

The success of any PFAS remediation strategy is fundamentally dependent on the availability of robust, efficient, and sensitive analytical methods. Accurate data is the bedrock upon which contamination is diagnosed, solutions are designed, and clean-up efforts are validated. Innovations in analytical chemistry directly enhance remediation capacity. For instance, methodologies that integrate QuEChERS extraction with a novel Enhanced Matrix Removal (EMR) mixed-mode passthrough cleanup have demonstrated significant practical advantages for analyzing biological tissues, which are critical for assessing ecological exposure and food safety [78].

The efficiency of such modern methods addresses a primary constraint in large-scale environmental monitoring: laboratory throughput. Compared to more labor-intensive traditional procedures [79], these streamlined approaches can reduce sample preparation time by over 80% and solvent consumption by more than 50%. This accelerated capability is crucial for remediation projects, where timely data is essential to delineate contamination plumes, assess ecological risks, and evaluate the effectiveness of cleanup actions on wildlife populations [78]. Furthermore, the exceptional repeatability of these methods, with over 90% of PFAS targets exhibiting less than 10% relative standard deviation (RSD), ensures the generation of highly reliable data, thereby reducing uncertainty in critical decision-making processes throughout a remediation lifecycle [78, 80].

The superior sensitivity of advanced methods is particularly consequential for setting and verifying remediation goals. The ability to reliably quantify PFAS at a validated limit of quantitation (LOQ) of 0.05 ng/g in fish and meat tissues ensures that monitoring can keep pace with increasingly stringent regulatory thresholds [78]. This high sensitivity is indispensable for demonstrating that contaminant levels have been successfully reduced to the sub-parts-per-trillion concentrations now required, such as the European Commission's standard of ≤ 0.1 ng/g for critical PFAS like PFOA, PFNA, PFHxS, and PFOS in food products [81, 82].

Moreover, the comprehensive cleanup afforded by advanced sample preparation techniques minimizes matrix effects, yielding more accurate and precise quantitation. This reliability allows for a definitive assessment of baseline contamination, the identification of predominant PFAS compounds, and the precise tracking of concentration changes over time [78]. Finally, simplified workflows reduce the potential for procedural errors and contamination, which is vital for generating legally defensible data. By empowering a broader range of laboratories to perform high-quality PFAS analysis, these advanced methods expand global monitoring capacity, thereby supporting more informed and effective remediation outcomes [78].

2. Analytical Methods for PFAS Monitoring in Complex Matrices

The development and validation of effective remediation technologies are intrinsically linked to the ability to accurately detect and quantify PFAS at trace levels in diverse and complex samples. Robust analytical methods are essential for characterizing contamination sources, monitoring treatment efficiency, and assessing risks to human health, particularly through food chain exposure. Advanced liquid chromatography-tandem mass spectrometry (LC-MS/MS) has emerged as the gold standard for this purpose, with methods capable of achieving sensitivities in the parts-per-trillion (ppt) range in complex food matrices such as milk, eggs, butter, cheese, and fish. This high sensitivity is critical for accurately mapping bioaccumulation pathways and ensuring food safety [83].

These analytical protocols often employ a multi-step sample preparation process to ensure accuracy and minimize matrix interference. A QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) extraction is typically used as an initial step to efficiently isolate PFAS from complex sample matrices, providing reliable quantitation at low parts-per-billion (ppb) levels. For even greater sensitivity and cleaner extracts, a subsequent solid-phase extraction (SPE) clean-up using mixed-mode sorbents can be implemented. This two-pronged approach enables accurate measurement down to 0.1 ng/g (ppt) even in challenging, high-fat foodstuffs, ensuring data integrity for risk assessment [83]. The selection of LC columns and mobile phase modifiers, such as ammonium formats, is also optimized to enhance ionization efficiency, maximize sensitivity, and maintain the chromatographic resolution of branched PFAS isomers, which is vital for accurate fingerprinting [83].

3. The Influence of Soil Organic Matter on PFAS Fate and Remediation

The efficacy of any in-situ or ex-situ soil remediation strategy is preconditioned by the bioavailability and mobility of the contaminant. For PFAS in soil systems, soil organic matter (SOM) acts as a primary sink, but its role is complex and extends beyond mere quantity. Research demonstrates that the chemical composition of SOM is a decisive factor in PFAS sorption and potential leaching. Studies utilizing 13C NMR spectroscopy have shown that PFAS sorption is strongly driven by the hydrophobic components of SOM, such as alkyl chains and lipids [84]. Soils enriched with highly hydrophobic organic matter, including polycyclic aromatic hydrocarbons (PAHs), exhibit significantly higher PFAS sorption capacities compared to soils where SOM is dominated by more hydrophilic, carbohydrate-rich components. This critical finding explains why total organic carbon content alone is a poor predictor of PFAS retention; the qualitative nature of the organic matter is paramount [78, 84].

Furthermore, a reciprocal relationship exists where PFAS can actively alter SOM dynamics. The surfactant nature of PFAS can enhance the mobilization of dissolved organic matter (DOM) from the soil matrix. This mobilization is not uniform; it preferentially increases the release of hydrophobic aliphatic constituents, thereby altering the chemical composition of the leachate and making it more hydrophobic [84]. This PFAS-induced shift in DOM quality and quantity has profound implications: it can facilitate the co-transport of PFAS and other hydrophobic contaminants, potentially accelerating plume migration in groundwater and complicating remediation efforts by creating a more complex dissolved phase that must be addressed in pump and-treat systems.

4. Non-Destructive (Separation and Concentration) Techniques

The initial step in managing widespread PFAS contamination, particularly in water, often involves their physical separation from large volumes to reduce the volume requiring subsequent destructive treatment. Technologies such as granular activated carbon (GAC) and ion exchange (IX) resins are widely deployed for this purpose, especially in treating drinking water and groundwater where contaminant concentrations are at parts-per-trillion levels [85-87]. These processes effectively partition PFAS from the aqueous phase, producing a purified water stream and a concentrated waste residual. This residual, often termed still bottom (SB) or brine, contains PFAS at parts-per-million levels alongside other concentrated salts and organic compounds [88, 89]. While separation is crucial for mitigating immediate exposure, it does not constitute destruction; the resulting high-strength waste requires further processing to prevent re-release into the environment, thereby creating a critical need for efficient destructive technologies [89, 90].

5. Destructive Technologies

The ultimate goal of PFAS remediation is the complete mineralization of these compounds into inert products like fluoride ions (F^-) and carbon dioxide (CO_2). Among the various destructive methods investigated, incineration has been a traditional approach. However, significant concerns regarding the potential for incomplete combustion and the formation of toxic fluorinated byproducts have cast doubt on its efficacy and environmental safety [91, 92]. The United States Environmental Protection Agency (USEPA) has highlighted the uncertainties associated with PFAS destruction via incineration, prompting the vigorous exploration of alternative, more reliable technologies [80, 93].

Several advanced destructive methods have shown considerable promise. Supercritical water oxidation (SCWO) utilizes water above its critical point (374°C, 22.1 MPa) to create a homogeneous phase that rapidly oxidizes organic compounds, including PFAS [80, 91]. Plasmabased treatments generate a field of highly reactive species in an electrical discharge that can effectively break down PFAS molecules [92]. Similarly, photocatalysis and electrochemical oxidation leverage light energy and electrical currents, respectively, to produce powerful oxidants that can attack and dismantle PFAS structures [77, 94, 95]. While these technologies are promising at a laboratory or pilot scale, their scalability, long-term energy efficiency, and consistent reliability for diverse, real-world waste streams remain active and critical areas of research [96].

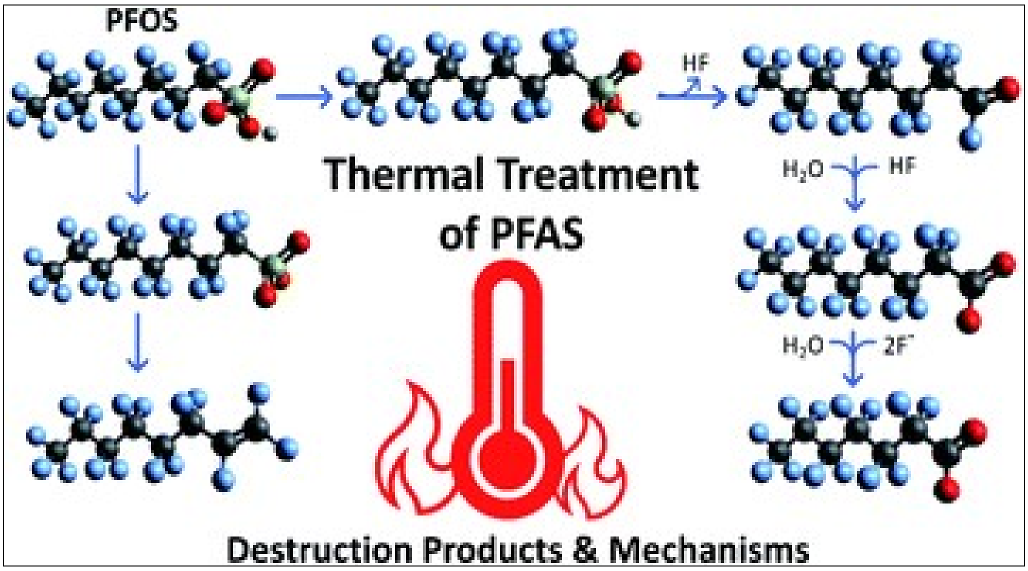

Fig 4: thermal treatment of PFAS [96].

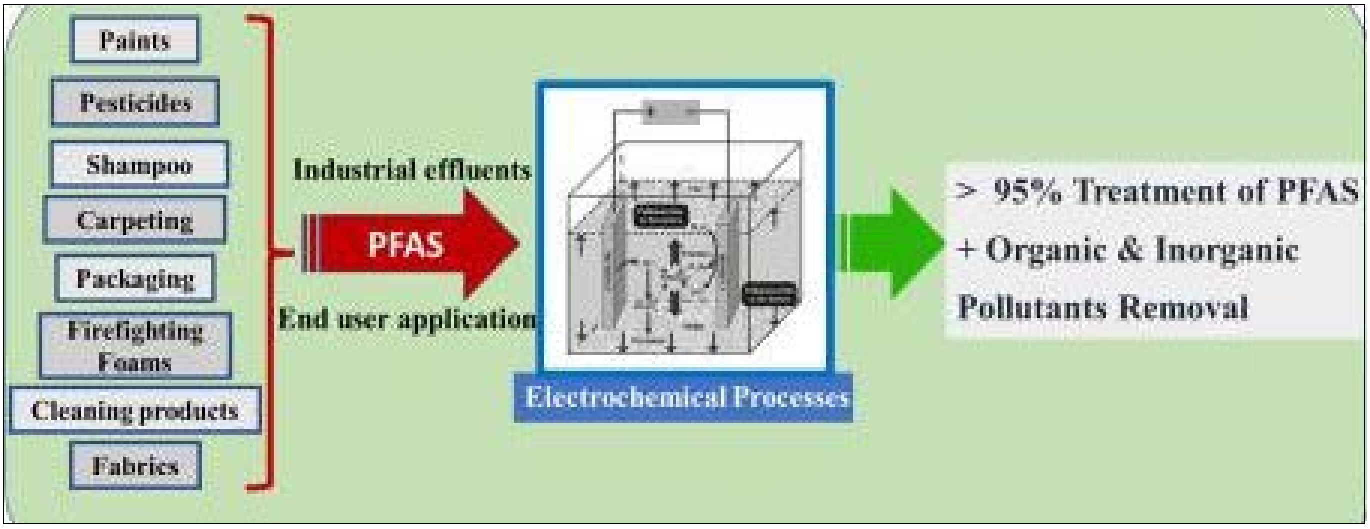

Fig 5: Electrochemical process for treatment of PFAS [6]

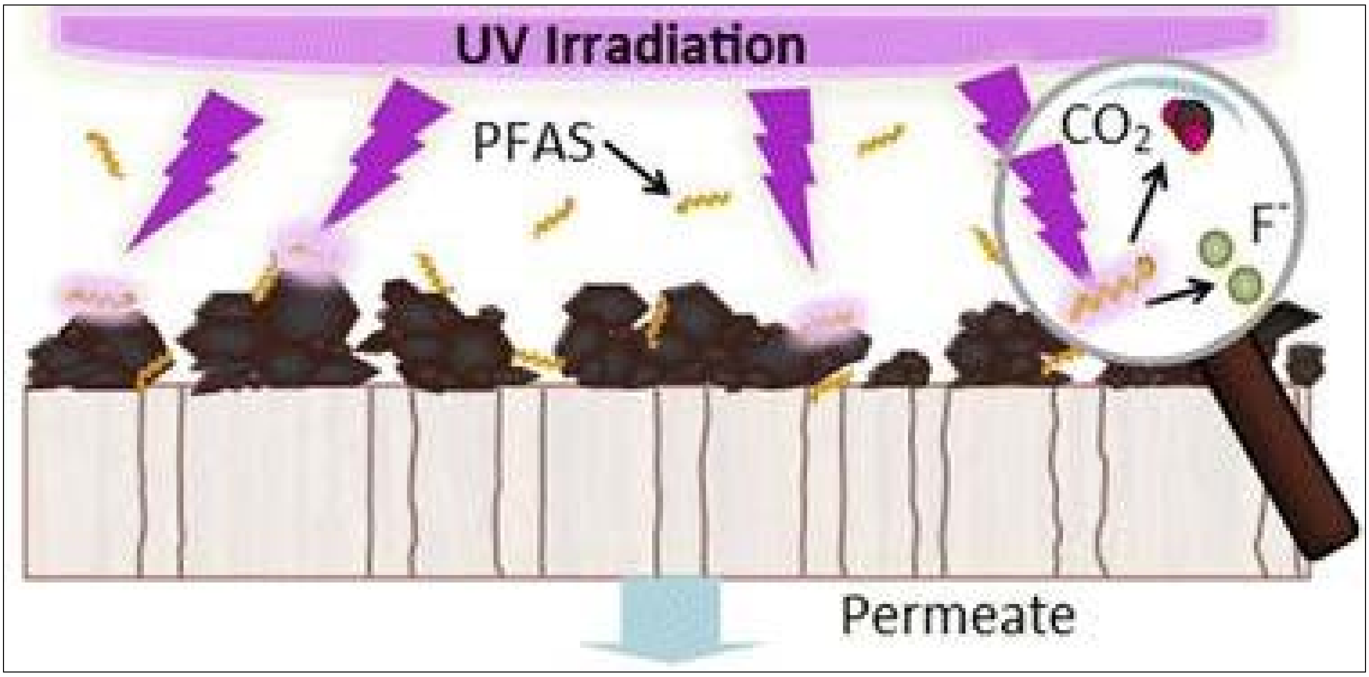

Fig 6: Adsorbation photocatalysis for treatment of PFAS [22]

6. Ultrasound Technology (Sonolysis) as a Remediation Tool

Sonolysis has emerged as a particularly compelling technology for PFAS destruction due to its unique mechanism of action. Unlike gas-phase incineration, sonolysis operates in the liquid phase at ambient bulk temperature, leveraging the phenomenon of acoustic cavitation. When high-frequency ultrasound is applied to a liquid medium, it generates and collapses micro- to nano-sized bubbles in a cyclical process. The implosion of these cavities creates transient, localized hotspots with extreme conditions, temperatures exceeding 5000 K and pressures over 500 bar [79, 90]. Within these microscopic reactors, PFAS molecules, which are surface-active, accumulate at the bubble-water interface and undergo pyrolytic cleavage of their strong C–F bonds, leading to mineralization into F^-, CO_2, and inorganic sulfur species in the case of sulfonates[97, 98]. Recent research demonstrates the practical application of multi-frequency ultrasonic reactors for treating complex PFAS-laden matrices. This technology has shown high degradation efficiency for groundwater and still bottom samples, with significant fluoride ion release confirming meaningful defluorination [99]. However, its performance can be significantly hindered in aqueous film-forming foam (AFFF) matrices, which are characterized by high concentrations of resistant PFAS like PFOS and abundant co-pollutant surfactants that cause excessive foaming. This foam layer physically impedes ultrasonic transmission and cavitation efficiency, while the high chemical oxygen demand (COD) from organic surfactants competes for the reactive radicals generated during sonolysis [99]. Energy consumption analyses provide critical insights for remediation planning, revealing that ultrasound treatment is most energy-efficient for concentrated still bottoms, while the energy demand is substantially higher for complex AFFF, underscoring the profound impact of matrix composition on process viability [99].

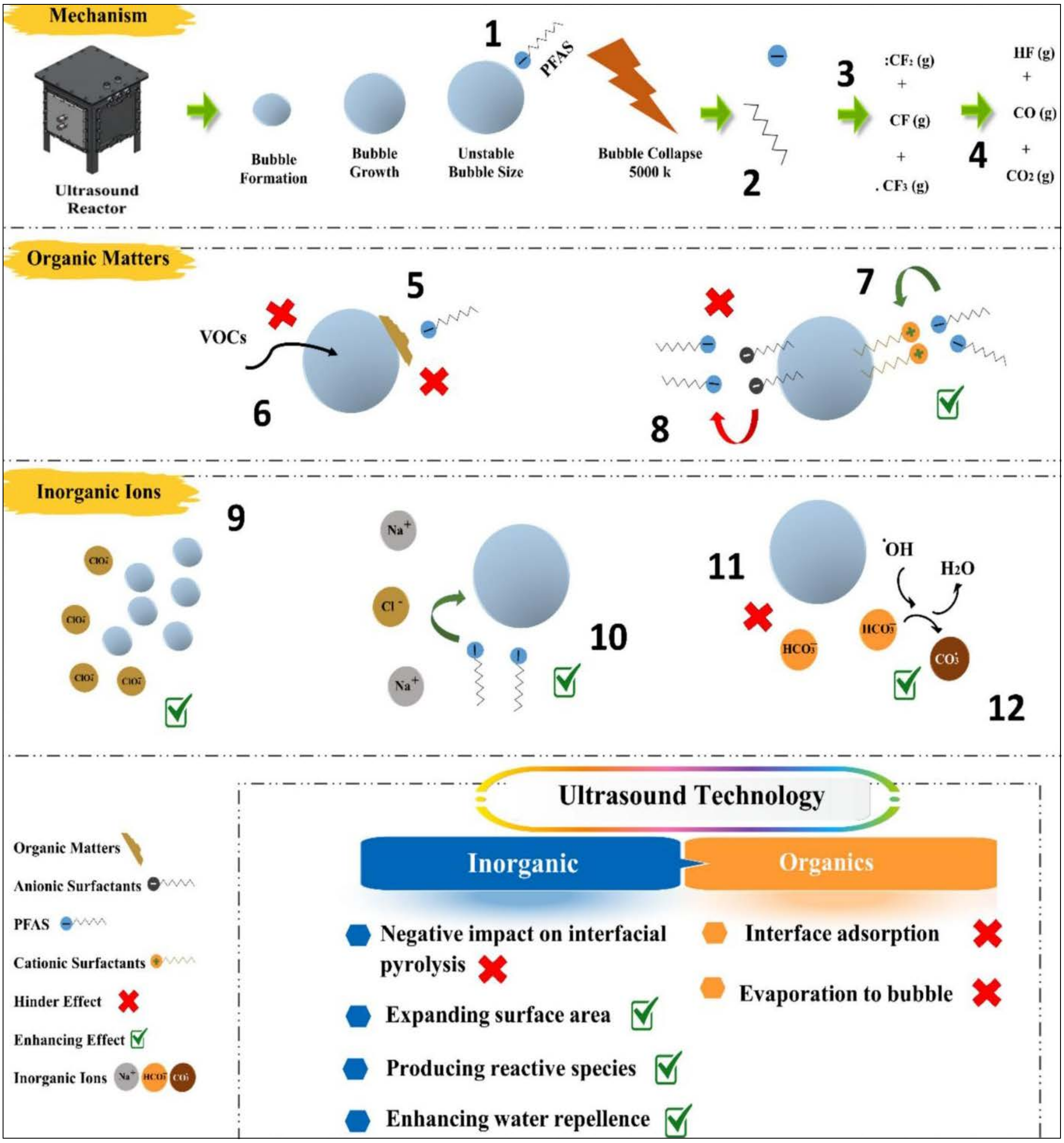

Fig 7: Effects and Mechanisms of ultrasound technology on PFAS degradation and interaction with inorganic ions and organic matter [99]

7.6. Emerging and Integrated Systems

Given the limitations of standalone technologies, the future of PFAS remediation lies in integrated treatment trains. These systems synergistically combine a non-destructive technique to concentrate PFAS with a subsequent destructive technology to degrade the concentrate efficiently. For example, coupling ion-exchange resin with electrochemical oxidation (IXR-EO) has been successfully piloted, achieving high destruction rates with improved energy efficiency by treating a much smaller, highly concentrated volume [87]. Similarly, to address the challenges of treating AFFF with sonolysis, integrated trains are being explored. Pre-treatment steps to reduce COD or mitigate foam, perhaps through chemical addition or mechanical means, could enhance the efficacy of subsequent sonolytic treatment. Furthermore, coupling sonolysis with other advanced oxidation processes (AOPs) may create synergistic effects, improving overall degradation kinetics and mineralization efficiency for the most recalcitrant PFAS compounds [99]

Discussion

The extensive evidence synthesized in this review paints a sobering picture of the per- and polyfluoroalkyl substances (PFAS) dilemma, a challenge born from a fundamental paradox: the very molecular robustness that made these compounds immensely valuable for industry and consumer products is the root of their intractable environmental persistence and associated health risks. This discussion integrates the multifaceted evidence presented on the historical trajectory, environmental pathways, human health impacts, analytical methodologies, and remediation technologies to distill overarching themes, identify critical interdependencies, and underscore the pressing need for a paradigm shift in how society manages such persistent chemicals.

A primary conclusion that emerges is the profound disconnect between the scale of PFAS production and use and the understanding of their long-term environmental fate. Initially developed for specialized applications like the Manhattan Project, PFAS were rapidly integrated into a vast array of consumer goods and industrial processes with limited consideration for their lifecycle [5, 8]. This historical legacy has resulted in a contamination footprint that is both global and pervasive, as confirmed by environmental surveys from industrialized hubs to pristine remote locations like the Arctic and high-altitude glaciers [6, 24]. The environmental mobility of PFAS, facilitated by their solubility and the atmospheric transport of volatile precursors, means that contamination is no longer a localized issue confined to point sources. Instead, it has become a diffuse problem, with multiple and cumulative exposure pathways for human populations, primarily through contaminated drinking water and the food chain [9, 10]. The case of the Saudi Arabian Red Sea, where wastewater effluent creates significant contamination hotspots, exemplifies how localized anthropogenic pressures can disrupt even vast marine ecosystems [41]. The translation of this widespread environmental presence into a human health burden is unequivocally supported by a substantial body of toxicological and epidemiological research. The health effects associated with PFAS exposure are notably systemic, impacting critical biological functions. The immunotoxic effects, particularly the dampened antibody response to vaccines in children, are especially alarming as they suggest a broad weakening of population-level resilience to infectious diseases [14, 42]. Furthermore, the associations with endocrine disruption, metabolic dysregulation such as dyslipidemia, and elevated risks for certain cancers point to the ability of PFAS to interfere with fundamental cellular signaling pathways, including those mediated by receptors like PPAR [14, 15, 50]. A particularly concerning aspect is the potential for latent effects, especially from prenatal and early-life exposure, implying that the full spectrum of public health consequences from decades of PFAS use may not be fully realized for years to come [15, 55].

The discussion on analytical methods and remediation technologies reveals a field in rapid, yet challenging, evolution. The gold-standard technique of LC-MS/MS has been instrumental in uncovering the true extent of PFAS contamination at parts-per-trillion levels, while non-targeted analysis using HRMS is crucial for identifying the myriad of emerging and unknown compounds that escape conventional monitoring [63, 75]. This analytical capability is not merely diagnostic; it is foundational to effective remediation. The data generated guides the delineation of contamination plumes, the selection of appropriate technologies, and the validation of their efficacy, particularly for destructive methods that aim for complete defluorination [78, 80]. However, the analytical complexity is matched by the remediation challenge. While established separation techniques like GAC and IX are vital for immediate exposure control in water treatment, they are inherently transitional solutions, transferring the problem from a dilute aqueous phase to a concentrated solid waste that requires secure disposal or further destructive treatment [85, 87].

The advancement of destructive technologies represents the most promising pathway toward a permanent solution. Methods such as supercritical water oxidation, sonolysis, electrochemical oxidation, and advanced reduction processes leverage extreme conditions or highly reactive species to break the resilient C–F bond [76, 80, 92, 99]. However, their performance is highly matrix-dependent. For instance, the efficiency of sonolysis is significantly hampered in complex matrices like AFFF due to foaming and competing organic loads, while the effectiveness of many oxidation processes can be scavenged by natural organic matter [84, 99]. This underscores that a "one-size-fits-all" remediation technology is unlikely. The future instead lies in intelligent treatment trains that strategically combine technologies. A promising approach is the "concentrate-and-destroy" strategy, such as coupling ion exchange with electrochemical oxidation, which improves energy efficiency by focusing destructive power on a small, highly concentrated volume [87]. Similarly, the development of materials capable of simultaneous adsorption and in-situ destruction, such as adsorptive photocatalysts, offers an elegant solution to the waste handling problem [72, 100, 101].

Finally, the regulatory and policy landscape is struggling to keep pace with the scientific understanding. The historical pattern of regulating individual compounds like PFOA and PFOS has inadvertently fueled a "regrettable substitution" cycle, where phased-out substances are replaced by other PFAS with similar persistence but less understood toxicological profiles [2, 3, 21]. This reactive approach is fundamentally inadequate for a class of thousands of related chemicals. There is a compelling and growing argument for managing PFAS as a single class, based on their shared property of extreme persistence, which would prevent such future regrettable substitutions [2, 44]. The stark disparities in international regulatory standards further complicate global management efforts and create inequities in public health protection. In conclusion, resolving the PFAS crisis demands an integrated, multi-pronged strategy that operates on parallel fronts. Technological innovation in remediation must be accelerated, with a focus on enhancing the scalability, energy efficiency, and cost-effectiveness of destructive technologies. This must be coupled with a proactive and preventative policy that restricts nonessential PFAS uses and promotes the development of genuinely safer alternatives. Continuous investment in advanced environmental monitoring and human biomonitoring is essential to track exposure trends, identify emerging contaminants, and evaluate the effectiveness of interventions. Ultimately, the PFAS saga serves as a critical lesson, highlighting the imperative for a precautionary approach in the introduction and management of persistent chemicals, urging a transition towards a circular economy where materials are designed for safety and sustainability across their entire lifecycle.

Conclusion and Recommendations

Conclusion

This integrated review has systematically charted the life cycle of per- and polyfluoroalkyl substances (PFAS), from their genesis as industrial marvels to their current status as a pervasive environmental and public health crisis. The evidence unequivocally confirms that the defining characteristic of PFAS—the ultra-robust carbon-fluorine bond—is the source of both their historical utility and their intractable environmental persistence. This "forever chemical" nature has facilitated their global dissemination, with contamination documented from densely populated industrial zones to the pristine environments of the Arctic and high-altitude glaciers, underscoring a pollution problem of planetary scale.

The pathways of human exposure are now well-established, primarily through contaminated drinking water and the food chain, leading to the near-universal presence of PFAS in human serum. A substantial and compelling body of toxicological and epidemiological evidence links this exposure to a spectrum of serious health outcomes. The most sensitive effects include immunotoxicity, notably reduced vaccine response in children, as well as endocrine disruption, metabolic dysregulation, and adverse developmental impacts. The latency and potential for cumulative damage from chronic, low-level exposure mean the full public health burden may not be realized for years to come.

In response, the scientific community has made significant strides. Advanced analytical methods, particularly LC-MS/MS and high-resolution mass spectrometry, now allow for the detection of these contaminants at the parts-per-trillion levels required by stringent new regulations. Simultaneously, the remediation landscape is evolving from mere containment via adsorption techniques toward transformative, destructive technologies. Processes such as advanced oxidation/reduction, electrochemical destruction, sonolysis, and supercritical water oxidation represent a paradigm shift, offering the promise of complete mineralization. However, these solutions are often challenged by high energy demands, matrix effects, and scalability issues, particularly when confronted with complex waste streams like AFFF.

The historical pattern of regulating PFAS one compound at a time has proven inadequate, leading to a cycle of "regrettable substitutions" where phased-out compounds are replaced by other persistent fluorinated alternatives. Therefore, mitigating the PFAS challenge demands a fundamental shift in strategy. It requires an integrated, multi-faceted global response that couples aggressive source control with innovative remediation, underpinned by robust monitoring and a precautionary regulatory framework that addresses PFAS as a single class of concern.

Recommendations

The synthesis of knowledge in this review reveals not only the scale of the PFAS challenge but also critical gaps in our current scientific, technological, and regulatory approaches. To move from problem characterization to effective solutions, the following targeted recommendations are proposed for researchers, regulators, and industry stakeholders.

1. **Shift from Targeted to Holistic Mixture Risk Assessment:** Future toxicological and epidemiological studies must prioritize the investigation of complex PFAS mixtures, as they occur in real-world environments. Research should move beyond the legacy PFOA/PFOS paradigm to define the toxicity, bioaccumulation potential, and health impacts of emerging alternatives and their transformation products. This requires developing robust testing frameworks that can evaluate synergistic or additive effects, which is fundamental for establishing protective, health-based standards that account for total PFAS exposure rather than individual compounds.

2. **Accelerate the Development of Sustainable and Selective Sorbents:** While adsorption is a critical first step, next-generation materials are needed. Research should focus on designing and scaling cost-effective sorbents with high selectivity for short-chain and ether-based PFAS (e.g., GenX), which are less effectively removed by conventional activated carbon. Furthermore, the development of "regenerable-by-design" materials, where PFAS are not merely concentrated but destroyed during the regeneration process (e.g., electrochemically active or photocatalytic media), should be a top priority to break the cycle of creating concentrated waste streams.

3. **Engineer Energy-Optimized and Scalable Hybrid Treatment Trains:** Given that no single technology is a panacea, research and pilot-scale funding must be directed toward optimizing integrated "concentrate-and-destroy" systems. This involves engineering smart treatment trains that intelligently couple separation technologies (e.g., ion exchange, nanofiltration) with the most appropriate destructive method (e.g., sonolysis, electrochemical oxidation) for a specific waste stream (e.g., AFFF, landfill leachate, still bottoms). A key focus should be on reducing the overall energy footprint and operational costs through process optimization and the use of renewable energy sources to make destruction technologies viable for widespread application.

4. **Implement Advanced Monitoring and Predictive Modeling in Vulnerable Regions:** For water-scarce nations like Saudi Arabia, proactive management is paramount. This necessitates the establishment of high-resolution, ongoing monitoring programs in critical water bodies, such as the Red Sea and key groundwater aquifers, using both targeted and non-targeted analytical methods. This data should feed into predictive hydrological and geochemical models to forecast contamination plumes, identify potential threats to desalination plants, and inform strategic land-use planning to protect vital water resources from future contamination.

5. **Establish Longitudinal Studies on Ecological and Human Health in Hotspots:** To fully understand the long-term consequences of PFAS contamination, longitudinal cohort studies must be initiated in well-defined geographic hotspots. These studies should track ecological endpoints (e.g., biodiversity shifts, reproductive health of key species) in parallel with human biomonitoring (e.g., serum levels, specific health outcomes in local communities). This integrated "One Health" approach is essential for quantifying the long-term impact, validating the effectiveness of remediation interventions, and providing irrefutable data to guide public health policy and resource allocation.

By championing these focused and innovative strategies, the global community can transition from a reactive stance to a proactive and comprehensive offensive against PFAS pollution, ultimately safeguarding environmental integrity and public health for generations to come.

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