Review Article

Per- and Polyfluoroalkyl Substances (PFAS) in Seafood Systems: Challenges, Health Impacts, and Remediation Strategies

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Abstract

Per- and polyfluoroalkyl substances (PFAS) are a diverse group of synthetic chemicals widely used in industrial and consumer applications for their hydrophobicity and chemical stability. These "forever chemicals" are persistent in the environment and have been increasingly detected in aquatic ecosystems and seafood, posing risks to food safety and public health. This review synthesizes current knowledge on PFAS chemical properties, contamination pathways in marine and aquaculture environments, and their bioaccumulation in seafood species. It also explores remediation technologies - including adsorption, ion exchange, membrane filtration, and advanced oxidation processes - alongside challenges in implementation. The review concludes by highlighting the need for integrated monitoring, regulatory controls, and risk mitigation strategies to address the global threat of PFAS in aquatic food systems.

Introduction

Per- and polyfluoroalkyl substances (PFAS) comprise a diverse class of over 12,000 synthetic chemicals characterized by a carbon–fluorine backbone, one of the strongest bonds in organic chemistry (Kwiatkowski et al., 2020). This structural stability confers exceptional environmental persistence, bioaccumulative potential, and resistance to degradation, leading to their widespread classification as "forever chemicals." PFAS have been extensively used in industrial and consumer products, including firefighting foams, nonstick cookware, food packaging, and textile coatings. Among these compounds, perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) are the most intensively studied and have been linked to a range of environmental and human health hazards [1,2] (Figure 1).

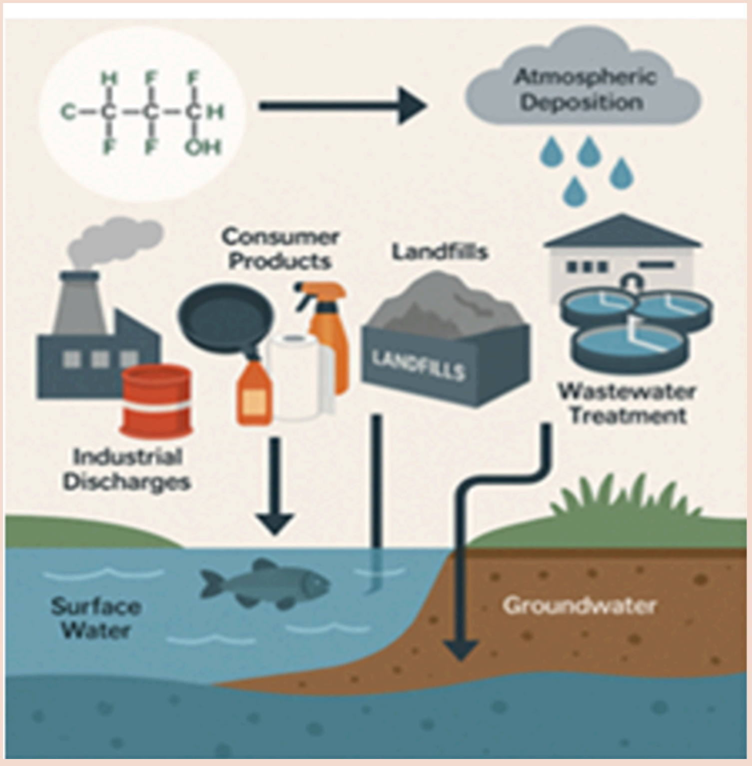

Figure 1: PFAS contamination pathways to seafood systems.

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PFAS contamination has been reported across various environmental matrices, including soil, groundwater, surface waters, sediments, and notably within the food chain - especially in seafood and aquaculture systems. Studies have documented PFAS accumulation in commercially important species such as clams, oysters, mussels, and finfish, raising serious concerns for both wild-caught and farmed seafood products [3,4]. Contamination in aquatic environments originates from point and non-point sources, including wastewater effluents, industrial discharge, landfill leachate, atmospheric deposition, and runoff from sites treated with aqueous film-forming foams (AFFFs) [5]. Due to their lipophilicity and environmental persistence, PFAS readily bioaccumulate in marine and freshwater organisms, with filter-feeding species being particularly susceptible due to sediment-associated exposures [6].

The presence of PFAS in both wild and farmed seafood products represents a significant food safety challenge. Numerous toxicological and epidemiological studies have identified PFAS as endocrine-disrupting compounds capable of altering lipid metabolism, immune function, and hormonal regulation [1,7]. Chronic dietary exposure has been associated with increased risks of kidney and testicular cancers, thyroid dysfunction, elevated cholesterol levels, reproductive toxicity, and neurodevelopmental effects in children [8].

Understanding the sources and distribution of PFAS in seafood and aquaculture systems, as well as their toxicological effects and mechanisms of action, is crucial for designing effective remediation and regulatory strategies. Equally important are efforts to support research innovation, strengthen policy frameworks, and implement public health interventions aimed at reducing dietary PFAS exposure and protecting the integrity of aquatic food systems.

PFAS Compounds and their Properties

PFAS represent a vast class of synthetic fluorinated chemicals distinguished by their unique chemical structure: A fully or partially fluorinated carbon chain bonded to various functional groups [9] (Figure 2). The hallmark of PFAS chemistry is the carbon-fluorine (C–F) bond, one of the strongest bonds in organic chemistry, exhibiting bond dissociation energies around 485 kJ/mol [10]. This bond imparts exceptional thermal stability, chemical inertness, and resistance to biodegradation, rendering PFAS persistent "forever chemicals" in the environment [11].

PFAS compounds are generally categorized based on the length of their perfluorinated carbon chain:

Long-chain PFAS typically have eight or more perfluorinated carbons (e.g., PFOA, PFOS). These compounds tend to be more bioaccumulative and toxic due to stronger hydrophobic and lipophilic interactions with biological membranes and proteins [12]. Their longer chains enhance binding affinity to serum proteins like albumin, facilitating retention in organisms and leading to longer biological half-lives [13,14].

Short-chain PFAS, with fewer than eight perfluorinated carbons (e.g., PFHxA, PFBA), generally exhibit higher aqueous solubility, reduced bioaccumulation potential, and shorter biological half-lives. However, they remain environmentally persistent and are more mobile in water systems, making them challenging to contain [15,16].

Functional groups attached to the perfluorinated chain influence the compound's behavior and toxicity. Carboxylates (-COOH) and sulfonates ($-SO_3H$) are common groups that confer ionic character, affecting PFAS sorption, transport, and bioavailability [17,18]. For example, PFOS, a sulfonate, often shows higher affinity for proteins and sediment organic matter than PFOA, a carboxylate [19,20].

PFAS compounds also include polyfluoroalkyl substances, where not all hydrogens on the carbon chain are replaced with fluorine, often serving as precursors to fully fluorinated PFAS through environmental transformation [21,22]. These precursors can degrade into terminal PFAS, complicating environmental monitoring and risk assessments.

The physicochemical properties of PFAS play a crucial role in their environmental behavior and biological interactions. Specifically, their low surface energy and amphiphilic nature - arising from a hydrophobic perfluorinated carbon tail and a hydrophilic functional head group (such as carboxylate or sulfonate) - allow PFAS to preferentially accumulate at various environmental interfaces, including air-water, sediment-water, and biological membranes. This interfacial activity is driven by the unique combination of chemical stability, lipophobicity, and strong C–F bonds that resist degradation [11,23]. For instance, at the air-water interface, PFAS act similarly to surfactants, reducing surface tension and concentrating at the interface, which enhances their transport through atmospheric deposition and rainwater washout [24-27]. At the sediment-water interface, PFAS partition depending on chain length and functional group polarity - long-chain PFAS with sulfonic acid groups (e.g., PFOS) tend to adsorb more strongly to sediments than short-chain variants [17,18,28]. Within biological systems, PFAS can associate

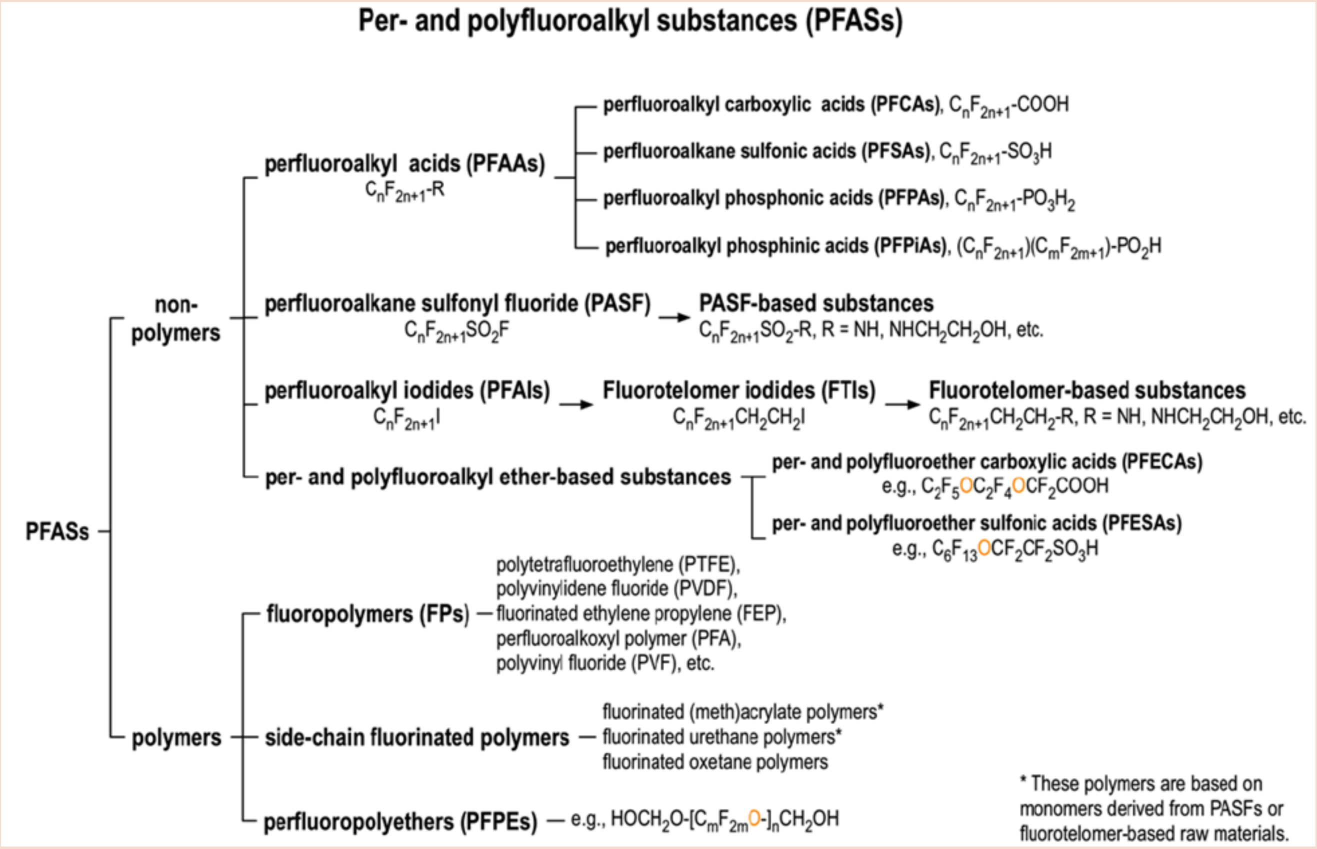

Figure 2: PFAS families of compounds (Organisation for Economic Cooperation and Development, 2015).

with membrane phospholipids and serum proteins such as albumin, disrupting cell function and leading to bioaccumulation and biomagnification through trophic levels [23,29,30,31]. Their persistence, mobility, and bioaccumulative potential are therefore closely linked to these interfacial behaviors, posing significant environmental and toxicological challenges.

Remediation Technologies and Mechanisms

Due to the chemical stability and environmental persistence of PFAS, remediation presents significant challenges. Most treatment strategies focus either on removal (separating PFAS from environmental media) or destruction (breaking the resilient C–F bonds). Below is a detailed overview of the primary remediation technologies and their underlying theory and mechanisms:

Granular Activated Carbon (GAC): GAC is a porous carbon material with high surface area and pore volume. PFAS molecules are adsorbed primarily through hydrophobic interactions between the fluorinated carbon chain and the nonpolar carbon surface of GAC, augmented by Van der Waals forces [32,33]. Long-chain PFAS with greater hydrophobic character adsorb more strongly, whereas short-chain PFAS, due to higher aqueous solubility, show weaker adsorption. Competing substances like natural organic matter can reduce adsorption capacity (Figure 3).

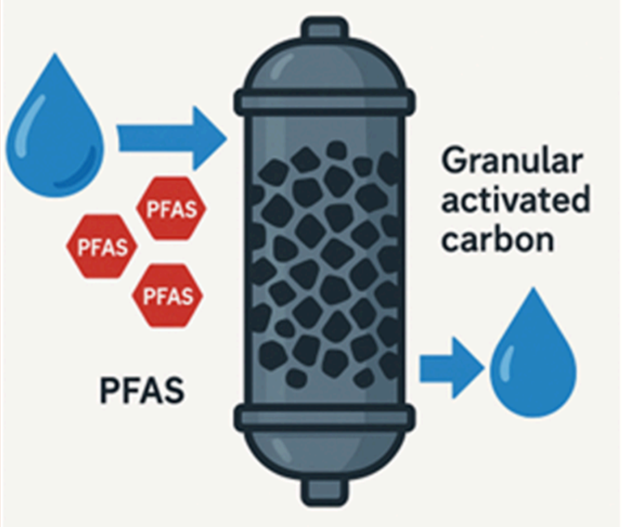

Figure 3: Granular activated carbon for PFAS remediation.

Ion Exchange Resins: These synthetic polymers contain charged functional groups (commonly positively charged quaternary ammonium groups) that electrostatically attract and bind negatively charged PFAS ions (carboxylates, sulfonates). This mechanism enables selective and efficient PFAS removal from water Carter et al., 2018, [34-36]. However, resins require periodic regeneration using concentrated salt solutions, generating PFAS-laden waste requiring further treatment (Figure 4).

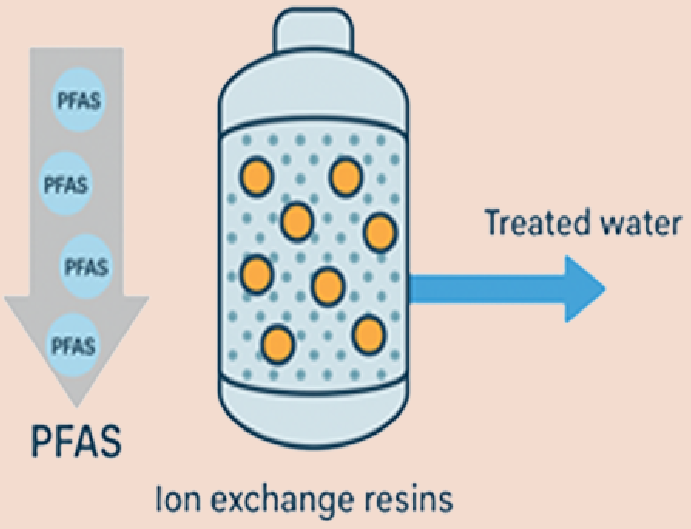

Figure 4: Ion exchange resins for PFAS remediation.

Membrane Filtration (Nanofiltration and Reverse Osmosis): These physical separation methods employ size exclusion and charge repulsion. Reverse osmosis membranes, with pore sizes below 1 nm, reject PFAS molecules primarily due to molecular size and charge interactions [37,38]. While effective, these technologies produce concentrated brine streams containing PFAS, which must be managed to prevent secondary pollution (Figure 5).

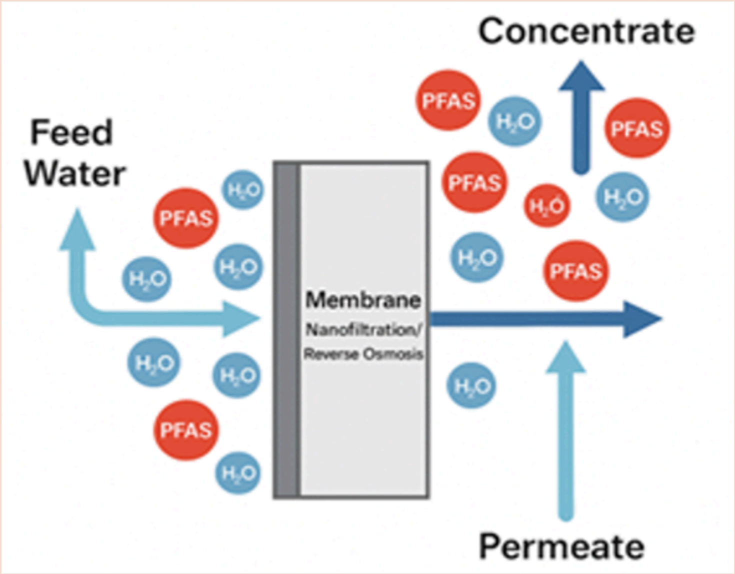

Figure 5: Ion exchange resins for PFAS remediation.

Advanced Oxidation Processes (AOPs): AOPs generate highly reactive radicals such as hydroxyl (•OH) and sulfate ($SO_4\bullet^-$) radicals through photochemical, catalytic, or electrochemical methods. These radicals attack PFAS molecules, breaking down functional groups and eventually cleaving the strong C–F bonds [39]. Typical AOP methods include UV/peroxide, ozonation, and electrochemical oxidation. Despite promising results, complete mineralization remains challenging and energy-intensive [40,41] (Figure 6).

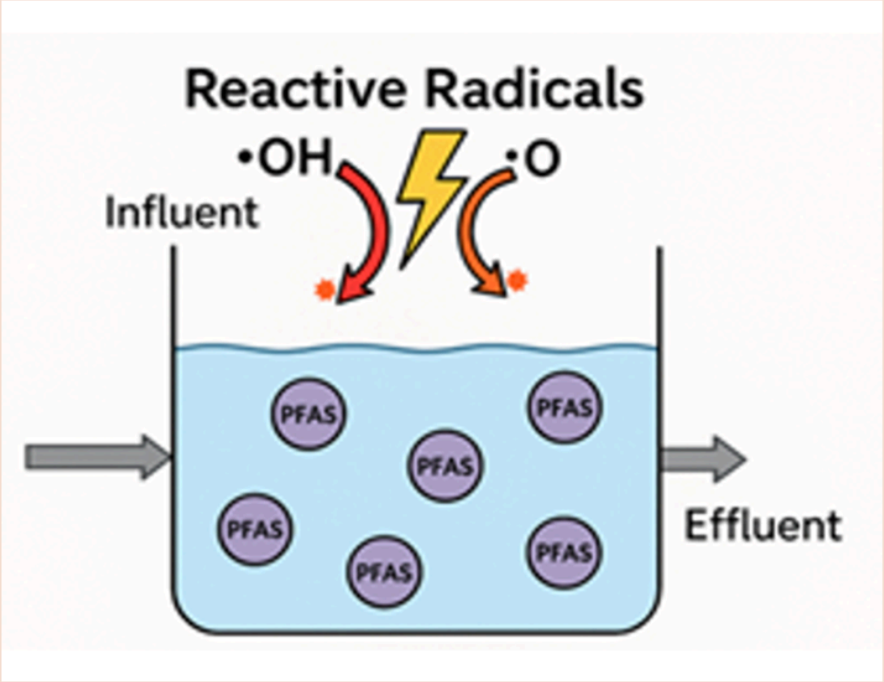

Figure 6: Advanced oxidation processes for PFAS remediation.

Electrochemical Oxidation (EO): EO uses specialized electrodes, such as boron-doped diamond (BDD), to produce oxidizing species directly at the electrode surface, enabling the cleavage of C–F bonds and mineralization of PFAS. EO avoids chemical additives but has high energy requirements and potential electrode degradation [42-44] (Figure 7).

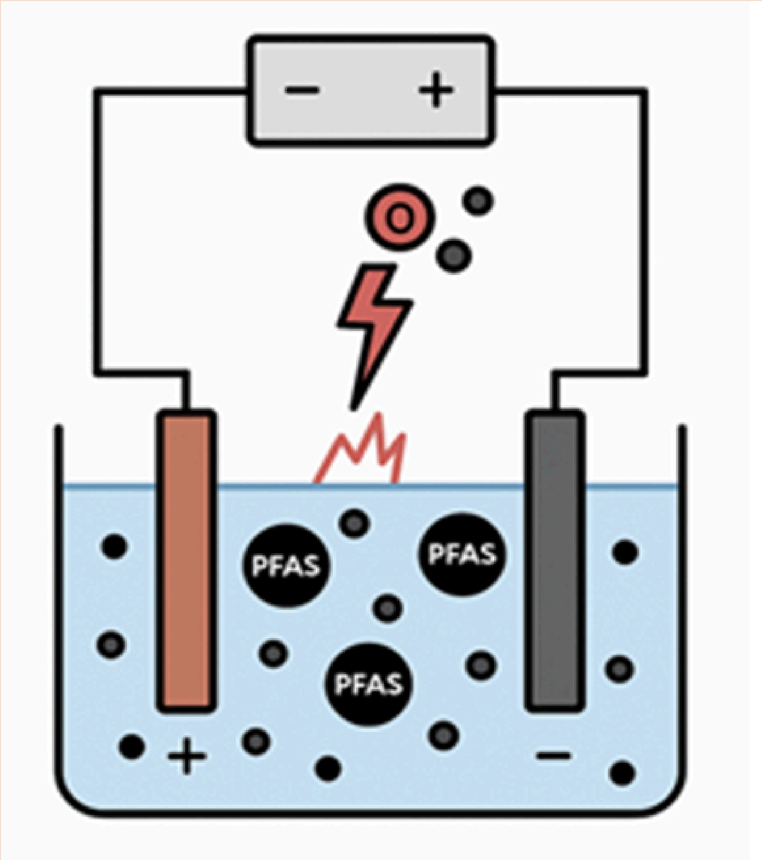

Figure 7: Electrochemical oxidation processes for PFAS remediation.

Thermal Destruction and Incineration: Thermal treatment at temperatures exceeding 1,000°C can break the resilient carbon-fluorine bonds, converting PFAS into less harmful gaseous products like CO_2 and HF. However, this method is energy-intensive and requires stringent controls to prevent toxic emissions [45,46].

Bioremediation and Phytoremediation: Biological degradation of PFAS is limited due to the strength of the C–F bond and lack of evolved enzymes. However, certain microbes (Acidimicrobium sp.) have shown reductive defluorination abilities under anoxic conditions [47]. Phytoremediation employs plants and algae to uptake PFAS from contaminated media, though these methods are experimental and require further development [48,49].

Plasma-Based Destruction Technologies: Plasma-based treatment is a promising emerging technology for the destruction of PFAS rather than mere separation or containment. Plasma, often referred to as the fourth state of matter, is a highly energetic ionized gas composed of free electrons, ions, neutral atoms, and reactive radicals. In plasma reactors, these reactive species are generated under high-voltage electric fields, typically within dielectric barrier discharge (DBD), corona discharge, or gliding arc discharge configurations.

PFAS compounds are resistant to most conventional degradation processes due to the extreme strength of the carbon–fluorine (C–F) bond. However, the reactive electrons and radicals in plasma can effectively cleave C–F and C–C bonds, initiating a series of oxidative and reductive reactions that result in stepwise defluorination and eventual mineralization of PFAS into carbon dioxide (CO_2), hydrogen fluoride (HF), and fluoride ions (F^-) [50-52].

Plasma processes are conducted either in dry (gas-phase) or wet (liquid-phase) conditions. Gas-phase plasma systems are effective for treating PFAS in off-gases or concentrated waste, while liquid-phase systems allow direct treatment of contaminated water. Recent advancements include plasma bubbling reactors, where gas-phase plasma is injected into water through a bubbler, enabling direct contact between reactive species and PFAS molecules [53].

One of the primary advantages of plasma treatment is that it does not require additional chemical reagents and generates minimal secondary waste. It also allows for on-site, point-of-use PFAS destruction, which is advantageous for managing highly contaminated effluents. However, challenges remain regarding energy consumption, electrode fouling, incomplete defluorination, and scalability for full-scale environmental applications (Figure 8) [54,55].

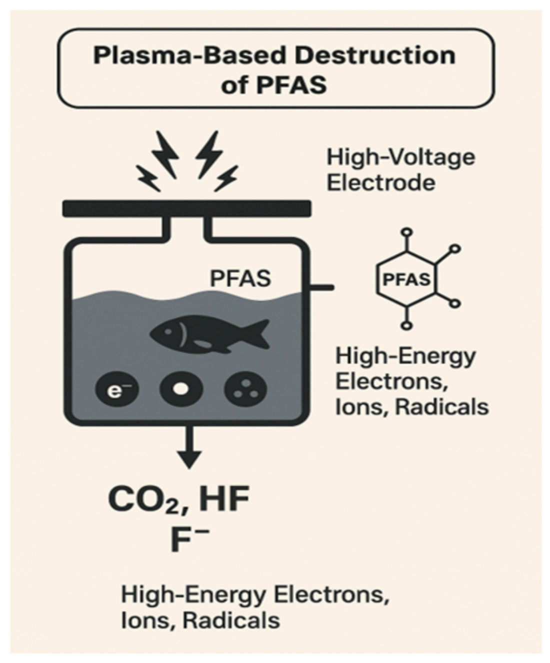

Figure 8: Plasma-based processes for PFAS remediation.

PFAS Presence in Seafood and Aquaculture Systems

PFAS have been increasingly detected in marine organisms, raising critical concerns for both environmental health and seafood safety. Due to their high chemical stability, resistance to degradation, and tendency to bioaccumulate, PFAS persist in aquatic environments and enter the food web through multiple exposure pathways [2,56,57].

Seafood species - particularly filter feeders (e.g., mussels, oysters, clams), bottom-dwelling organisms (e.g., crabs, lobsters), and predatory fish (e.g., salmon, cod, tuna) - are especially vulnerable to PFAS accumulation. These compounds are absorbed from contaminated water, sediments, and diet, and tend to concentrate in protein-rich tissues such as liver and muscle due to their affinity for serum albumin and phospholipids [58,59].

Recent studies have shown that seafood is among the most PFAS-contaminated food groups. According to the U.S. Food and Drug Administration (FDA), PFAS were detected in 74% of sampled seafood products, including shrimp, cod, tuna, salmon, and pollock National Academies of Sciences, Engineering, and Medicine, 2024) Notably, PFOS and PFOA are the most frequently reported compounds, often found at concentrations exceeding advisory limits set by regulatory agencies [60].

In aquaculture systems, PFAS contamination may result from contaminated feed, water sources, or proximity to industrial discharge points, wastewater treatment plants, or biosolid application zones [28,61].

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Farmed fish may accumulate PFAS directly through water or indirectly via feed containing contaminated marine ingredients (e.g., fishmeal, fish oil). Because recirculating aquaculture systems (RAS) often reuse water over long periods, even trace levels of PFAS can concentrate over time, increasing bioaccumulation risk in farmed species.

PFAS not only threaten seafood safety but also have economic and trade implications. Public concerns over contaminated products may reduce consumer confidence, and seafood producers face potential regulatory restrictions and testing burdens. In response, some governments have initiated monitoring programs and proposed maximum allowable levels of PFAS in seafood. However, global regulatory standards remain inconsistent, and more research is needed to evaluate PFAS dynamics in aquaculture environments and establish effective mitigation strategies.

PFAS Presence in Seafood and Aquaculture Systems

The accumulation of per- and polyfluoroalkyl substances (PFAS) in seafood is governed by a complex interplay of physicochemical properties, organismal physiology, and environmental exposure pathways. Unlike traditional lipophilic persistent organic pollutants (POPs), PFAS are amphiphilic, ionizable organic molecules that bind preferentially to proteins rather than lipids, leading to unique accumulation and distribution patterns in aquatic biota [59,62-65].

Physicochemical Properties Driving Bioaccumulation :

PFAS molecules, particularly legacy compounds such as PFOS and PFOA, possess both a hydrophobic perfluorinated carbon chain and a hydrophilic, ionizable head group (e.g., sulfonic or carboxylic acid). This amphiphilic character enables PFAS to:
a) Adsorb onto organic particles and suspended matter in the water column
b) Penetrate gill membranes due to moderate water solubility
c) Interact with plasma proteins, including albumin and binding globulins, through ionic and hydrogen bonding

Their low vapor pressure, high thermal stability, and resistance to metabolic and environmental degradation further facilitate persistence and accumulation in aquatic environments [11,23,66,67].

Environmental Exposure Pathways

Waterborne Uptake via Gills:

Gill membranes provide a large surface area for exchange of dissolved contaminants. PFAS uptake occurs via passive diffusion or facilitated transport across epithelial cells, depending on chain length, functional group, and ambient pH. Studies suggest that:

a) Short-chain PFAS (e.g., PFBA, PFHxA) exhibit higher mobility but lower bioaccumulation due to faster renal clearance.

b) Long-chain PFAS (≥C8 for PFCAs and ≥C6 for PFSAs) are more likely to accumulate in tissues due to strong protein binding and slower elimination [21,68,69,70].

Ingestion of Contaminated Prey and Sediment:

Benthic organisms and filter feeders ingest PFAS through sediment-associated particles or by filtering contaminated water. Trophic transfer becomes a dominant pathway for higher trophic level species, such as predatory fish, which accumulate PFAS through the consumption of smaller contaminated organisms [3,71,72].

Aquaculture Feed and Recirculating Systems: In controlled aquaculture environments, PFAS may enter through:
a) Contaminated feed ingredients, such as fishmeal or krill oil
b) Make-up water sources contaminated from industrial or wastewater inputs
c) Recirculating aquaculture systems (RAS), where low-level PFAS can concentrate over time due to water reuse

This introduces both direct dietary exposure and chronic background exposure, increasing PFAS burdens even in farmed seafood [6,73,74].

Tissue-Specific Distribution and Binding Mechanisms

Unlike lipophilic pollutants that partition into fat, PFAS compounds preferentially bind to proteins and accumulate in blood-rich tissues. The underlying mechanisms include:
a) Electrostatic interactions between negatively charged PFAS headgroups and positively charged amino acid residues in serum proteins (e.g., arginine, lysine)
b) Hydrophobic interactions of the fluorinated tail with lipid membranes and phospholipids
c) Carrier protein transport, including binding to albumin, transthyretin, and fatty acid-binding proteins (FABPs), which facilitate systemic distribution (Han et al., 2003) [75-77].

Common sites of accumulation in fish and shellfish include:
a) **Liver:** high levels of metabolic enzymes and blood flow promote accumulation
b) **Kidney:** involved in excretion, but also serves as a retention site
c) **Muscle:** important from a dietary exposure perspective, although PFAS levels are typically lower than liver [78,79].

Bioaccumulation and Trophic Transfer Potential

PFAS bioaccumulation is influenced by:
a) Carbon chain length: Longer-chain PFAS (e.g., PFOS, PFNA) exhibit greater bioconcentration and slower elimination.
b) Trophic level: Top predators (e.g., tuna, swordfish, sharks) show elevated PFAS levels due to biomagnification.
c) Species-specific physiology: Metabolism rate, kidney function, and gill morphology influence PFAS retention [80-82]

Studies have documented biomagnification factors (BMFs) and trophic magnification factors (TMFs) >1 for PFOS in several marine food webs, indicating the potential for upward transfer through trophic levels - though less so than with lipophilic POPs [83-85].

Lack of Effective Elimination Pathways

Once internalized, PFAS are poorly metabolized and inefficiently excreted, particularly in fish, where renal elimination is limited. The renal transporters involved in PFAS excretion (e.g., organic anion transporters, OATs) are saturable, and in some species, functionally less active. This leads to:
a) Long biological half-lives (months to years)
b) Continuous accumulation under chronic exposure

Some fish species (e.g., rainbow trout) have shown PFOS half-lives ranging from 30 to 90 days, depending on water concentration and temperature [86].

PFAS Mitigation in Seafood Systems

Reducing PFAS contamination in seafood and food systems requires integrated strategies across the supply chain:

a) Monitoring and Surveillance: Routine testing of seafood products, sediments, and water sources helps identify contamination hotspots and assess risk levels.
b) Regulatory Controls: Phasing out the production and use of legacy PFAS (e.g., PFOS, PFOA) and regulating emissions from industrial sources are critical to limiting environmental release.
c) Consumer Guidance: Issuing advisories for seafood consumption, particularly for high-risk groups (e.g., pregnant women, children), helps mitigate dietary exposure (US EPA, 2023).
d) Alternative Packaging Materials: Eliminating PFAS-containing food contact materials (e.g., grease-resistant papers) can prevent indirect food contamination.
e) Aquaculture Management: Using clean water sources, filtered feed, and improved farming practices can minimize PFAS bioaccumulation in farmed seafood.
f) Source Control and Sediment Remediation: Intervening at pollution sources and remediating contaminated sediments through dredging, capping, or in-situ stabilization can reduce PFAS uptake by benthic organisms [87-90].

Conclusion and Future Perspectives

PFAS contamination in seafood and aquaculture systems poses a complex and urgent global challenge, demanding coordinated scientific, regulatory, and technological responses. Their physicochemical properties - particularly persistence, mobility, and affinity for proteins - facilitate their accumulation in aquatic species, resulting in significant food safety concerns and ecological risks. While several remediation strategies show promise - such as activated carbon adsorption, ion exchange, and advanced oxidation - no single method offers a comprehensive solution for all PFAS types across varying environmental matrices.

To safeguard public health and aquatic biodiversity, it is essential to enhance routine monitoring, establish enforceable regulatory standards, and phase out the use of high-risk PFAS compounds. Research efforts should prioritize scalable and cost-effective remediation technologies, mechanisms of PFAS toxicity in marine organisms, and effective risk communication strategies for consumers. By advancing interdisciplinary solutions, the scientific community can support more sustainable seafood systems and reduce the long-term burden of PFAS on ecosystems and society.

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