

Toxic-Free Environment: Forever Chemicals Removal from Water and Wastewater

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS), commonly known as "forever chemicals," are persistent synthetic compounds that have been widely utilized since the mid-20th century across various industries. Due to their environmental persistence and potential health risks, PFAS has become a significant concern, particularly in relation to water and wastewater contamination. This paper investigates the complex challenges associated with PFAS, focusing on existing regulatory frameworks, treatment strategies, and innovative clean technologies that aim to reduce or eliminate these harmful substances. The study emphasizes the importance of advanced treatment methods such as electrochemical degradation, nanofiltration, adsorption, and biodegradation, each offering varying degrees of success. Despite advancements in treatment technologies, prevention remains the most effective strategy to minimize PFAS pollution. The paper calls for collaborative efforts from regulatory bodies, industries, and communities to implement more sustainable practices, ensuring a toxic-free environment and aligning with circular economy principles. Continuous research and international cooperation are crucial for developing effective long-term solutions to address PFAS contamination and safeguard both public health and the environment.

1. INTRODUCTION

Forever chemicals, per- and polyfluoroalkyl substances (PFAS) are persistent organic pollutants of industrial origin. PFAS are known for their resilience, ability to accumulate in nature, and potential toxicity. These compounds are characterized as non-biodegradable, non-reactive, non-photolytic, and hydrolysis-resistant, rendering them recalcitrant in the environment [1,2]. Two of the most prominent PFAS compounds, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), have been widely detected in various environmental matrices, including drinking water, surface water, groundwater, and coastal water, raising significant public health and environmental concerns [3]. These chemicals are categorized by their carbon-chain length, with "long-chain" and "short-chain" distinctions [4,5]. While the extensive use of poly- and

perfluoroalkyl substances (PFAS) has a history dating back to the 1950s, it was only in the early 2000s, subsequent to the initial reports indicating the presence of PFAS in both wildlife and human serum, that scientific inquiries into their properties, occurrence, environmental fate, and health effects began to gain substantial momentum [6]. Over the past few decades, the prevalence of PFAS has become increasingly apparent, with their extensive detection across diverse environmental compartments. Nakayama et al. [7] underscore this widespread occurrence, characterizing PFAS as widely distributed in nearly all aquatic matrices, encompassing drinking water, surface water, groundwater, and coastal water [3,7].

A comprehensive understanding of the physicochemical properties of PFAS is crucial for predicting their environmental behavior and transport mechanisms. The melting and boiling points of these compounds determine whether they exist as solids, liquids, or gases under standard conditions [8]. Most PFAS are typically found in solid form, either crystalline or powdery, at atmospheric pressure. However, shorter-chain PFAS, with carbon chain lengths between 4 and 6, are more likely to be liquids. For example, the melting point of perfluorobutanesulfonic acid (PFBS) is -21°C , while perfluorooctanoic acid (PFOA) has a melting range of 45°C to 54°C [9]. The density of liquid-phase PFAS at ambient temperatures affects their environmental dynamics [10,11]. To date, only a handful of well-characterized PFAS compounds, including perfluorinated carboxylic acids (PFCAs), perfluorooctane sulfonate (PFOS), and fluorotelomer alcohols, have experimentally determined water solubility data [10].

The long-lasting nature of forever chemicals raises concerns about their environmental and health impacts. PFAS are linked to health risks, ranging from acute to chronic conditions. Studies have reported potential links between PFAS exposure and thyroid disorders, asthma, anxiety, obesity, pediatric allergies, hyperuricemia, peroxisome proliferation, immune toxicity, kidney disorders, liver damage, cancer, immune system dysfunction, developmental disorders, and cardiovascular diseases [12-14]. Recent studies have also revealed their presence in food products, contributing to concerns about dietary exposure. Human exposure occurs through various sources, such as contaminated food, drinking water, inhalation of air and dust, and PFAS-containing products [3,15,16]. While some long-chain PFAS have faced restrictions, the production of short-chain PFAS and alternative variants has increased. Furthermore, examinations of PFAS have expanded to encompass their effects on animal health. Research, as demonstrated by Poothong et al. [17] and Rand et al. [18], reveals toxic outcomes, encompassing immunotoxicity, carcinogenicity, and hormonal disorders. These effects are notably linked to perfluoroalkyl carboxylic acids (PFCAs) in animals.

In response to growing concerns, regulatory agencies such as the U.S. Environmental Protection Agency (EPA) have established health-based guidelines for PFAS concentrations in drinking water [19]. The EPA has set a lifetime health advisory level of 70 ng/L for the combined concentrations of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), and lower guidelines for short-chain PFAS C4–C7 range from 300 to 7,000 ng/L. However, there is increasing pressure for stricter regulations as the understanding of PFAS toxicity evolves.

The challenge of removing PFAS from water has become a critical focus for wastewater treatment plants (WWTPs), which are significant sources of PFAS contamination in aquatic environments, with industrial wastewater often having higher PFAS concentrations than domestic wastewater [20-27]. The removal of PFAS in WWTPs depends on influent concentrations [28], treatment processes [27], PFAS characteristics,

and the proportion of industrial wastewater [20,29]. PFAS can also enter the environment through atmospheric emissions [30] and the use of PFAS-contaminated sludge as fertilizer [31]. Extensive research has been conducted on PFAS in WWTP effluent and recipient waters [22,23,25,32].

The multifaceted aspects of per- and polyfluoroalkyl substances (PFAS) in the environment are comprehensively investigated in this paper. With a particular focus on regulatory frameworks, treatment strategies, clean technologies, and their potential integration into a circular economy, with a specific emphasis on the promotion of a toxic-free environment and alignment with the principles of the Green Deal.

2. PFAS AND THE GREEN DEAL FOR A TOXIC-FREE ENVIRONMENT

The European Green Deal is a comprehensive plan to make the European Union's economy sustainable and to achieve a toxic-free environment. The strategy is the first step towards a zero pollution ambition for a toxic-free environment. The European Green Deal and the toxic-free environment initiative concerning per- and polyfluoroalkyl substances (PFAS) are focused on diminishing the usage and exposure of these persistent chemicals across different products and processes. The 2020 Chemicals Strategy for Sustainability (CSS) identifies PFAS as a pressing concern necessitating immediate action, with the European Union (EU) actively working to restrict their use in fire-fighting foams. Aligned with the overarching goals of the Green Deal, which seeks climate neutrality and pollution reduction, there is an emphasis on addressing PFAS pollution. Despite these efforts, concerns have been raised about the EU potentially deviating from its commitment to banning non-essential hazardous chemicals, including PFAS, due to industry influence. The EU's regulatory framework, shaped by the European Green Deal, employs a comprehensive strategy involving risk assessment, management, and mitigation strategies. This includes the establishment of maximum allowable limits for PFAS in various environmental compartments, backed by rigorous scientific assessments incorporating evidence from research studies and monitoring programs evaluating PFAS occurrence and behavior in diverse environmental matrices [33, 34].

In February 2023, the Environmental Protection Agencies of Denmark, Sweden, Norway, Germany, and the Netherlands submitted a proposal to the European Chemical Agency (ECHA) advocating for a ban on the use of per- and polyfluoroalkyl substances (PFAS) [35]. This proposal was driven by recent evidence indicating significant issues with the transition to PFAS alternatives, resulting in widespread environmental contamination. Denmark led the way as the first country to ban PFAS, and now other EU nations are backing restrictions on these chemicals due to their carcinogenic, endocrine-disrupting, and immunotoxic properties. This proposal is one of the most comprehensive plans received by the ECHA in the past 50 years [36].

Regulatory agencies and researchers have intensified efforts to understand the sources, behavior, and pathways of PFAS in the environment [38, 39]. The release of PFAS into the environment occurs through multiple pathways. Diffuse sources such as atmospheric deposition and surface run-off contribute to environmental contamination [40, 41]. Other pathways include emissions from landfills [42, 43], discharge from wastewater treatment plants (WWTPs) [23, 44], and contamination from firefighter training facilities

[24, 45]. As a result, PFAS are ubiquitously present in the environment, even in sparsely populated regions [46, 47].

Table 1. Industry sectors and usage categories for PFAS, with subcategories indicated in parentheses [37].

Industry branches	
Aerospace Industry (7)	Mining Sector (3)
Biotechnology Sector (2)	Nuclear Industry
Construction and Building Sector (5)	Oil and Gas Industry (7)
Chemical Industry (8)	Pharmaceutical sector
Electrolysis and Plating Industry	Photographic Sector (2)
Electroplating Industry (2)	Plastics and Rubber Production (7)
Electronics Sector (5)	Semiconductor Industry (12)
Energy sector (10)	Textile Manufacturing (2)
Food industry	Watch-making industry
Machinery and Equipment Manufacturing	Woodworking Industry (3)
Metal Products Manufacturing (6)	

PFAS substances have found extensive use in both industrial and consumer products, owing to their distinctive attributes such as water and grease resistance. Historically, PFAS have been integral to a wide array of applications and products, including non-stick cookware, where they have been employed to create non-stick coatings, notably Teflon. They have also been instrumental in rendering fabrics stain and water-resistant, as seen in waterproof clothing, carpets, and upholstery [48]. In food packaging, PFAS have been utilized in items such as fast-food wrappers, microwave popcorn bags, and pizza boxes to prevent oil and grease penetration. Firefighting foams, featuring PFAS components like perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), have been employed to combat liquid fuel fires. Furthermore, PFAS have played a role in the electronics industry, particularly in the manufacturing of semiconductors and printed circuit boards, as well as in hydraulic fluids for their lubrication properties [48]. These compounds have even made their way into cosmetics and personal care products for their water-resistant qualities. Additionally, the medical field has harnessed PFAS, notably in manufacturing certain medical devices, including catheters and tubing, to improve their biocompatibility and durability. Furthermore, the chemical industry has utilized PFAS in various industrial processes, including the production of fluoropolymers and other chemicals [49], Table 1 provides a list of industry sectors and additional areas of application where PFAS have been or are currently in use [37].

However, it is essential to highlight that growing concerns regarding the environmental persistence and potential health risks associated with PFAS have prompted increased scrutiny and regulation across these applications. Consequently, concerted efforts are underway to reduce PFAS usage in certain products and to explore safer alternatives. Furthermore, several countries and regions have imposed restrictions and bans on specific PFAS compounds [4, 5, 30].

3. REGULATIONS AND FRAMEWORKS

The regulatory frameworks for PFAS in water and wastewater vary worldwide, with more stringent guidelines and standards being established in developed countries. The European Green Deal and the toxic-free environment approach aim to reduce the exposure to PFAS and other hazardous substances. In Turkey, specific regulations and standards for PFAS removal from wastewater and water are not well-defined, but there is a growing concern about the presence of PFAS in drinking water sources [19].

The regulatory frameworks for PFAS in water and wastewater can be summarized as follows:

Global: The United States Environmental Protection Agency [19] exercises broad enforcement discretion, allowing for potential exemptions for Publicly Owned Treatment Works (POTW) facilities. Nevertheless, it encourages states and municipalities to proactively identify known or suspected sources of PFAS and employ best management practices to address potential PFAS discharge [19].

Europe: The European Chemicals Agency (ECHA) has issued a proposal to restrict PFAS in various products, including textiles [19]. The European Green Deal and the toxic-free environment approach aim to reduce the exposure to PFAS and other hazardous substances, promoting environmental sustainability and reducing pollution [50]. On June 13, 2017, the European Union formally implemented Regulation (EU) No. 2017/1000, as published in the Official Journal. This regulatory measure delineates restrictions concerning perfluorooctanoic acid (PFOA), its salts, and related substances. The amendment introduced a novel entry, denoted as entry 68, to Annex XVII of the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) framework [33].

Turkey: Turkey introduced regulations on persistent organic pollutants, specifically focusing on substances like Perfluorooctane sulfonic acid and its derivatives (PFOS). Effective from November 14, 2018, the law prohibits the manufacture, market entry, and use of PFOS, emphasizing the reduction of emissions and proper waste management. The regulations mirror several provisions of the EU legislation but have distinct aspects. Notably, Turkey listed PFOS, along with other chemicals, imposing strict limits on their presence in substances, mixtures, articles, or parts thereof. The legislation demonstrates Turkey's commitment to addressing environmental concerns associated with PFOS, aligning with global efforts to regulate these persistent and harmful substances [50, 51].

Enhancements in PFAS removal technologies are required to optimize their efficiency and feasibility. The imperative lies in the establishment of regulatory compliances, coupled with the essential components of exposure assessment and risk characterization, to provide precautionary guidance about water source protection and the security of water supply.

4. IMPLEMENTING CIRCULAR ECONOMY FOR EFFECTIVE PFAS REDUCTION IN THE ENVIRONMENT USING BEST AVAILABLE TECHNIQUES

The circular economy, an emerging economic model committed to eliminating waste and pollution through the strategic design of products, holds significant promise for addressing the challenges posed by per- and polyfluoroalkyl substances (PFAS) in wastewater [52, 53]. Integrating the principles of Best Available Techniques [54] [54] for PFAS reduction, this approach emphasizes material recovery and reduction [54,

55]. Research consistently demonstrates that the circular economy can effectively curtail the extraction of primary resources, reducing the demand for raw materials and potentially diminishing the presence of PFAS in the environment [56].

Within the context of PFAS removal, the circular economy, along with Best Available Techniques [54], contributes to mitigation efforts in several ways:

Preventive Product Design: Aligning with the preventive principle, the circular economy discourages the production of PFAS-containing products. The promotion of designs and manufacturing processes free from PFAS and other hazardous substances directly reduces the potential environmental burden associated with PFAS release [57, 58].

Integrating Green Raw Materials: Green raw material in the circular economy is a clean technology for minimizing PFAS. This aligns with circular economy principles, reducing contamination risk and promoting sustainability. Applying the "keeping products in use" principle to these materials minimizes environmental impact and resource demand. Furthermore, adopting green raw materials supports natural system regeneration [59].

Advancements in PFAS Recovery and Recycling: Fostering progress in the recovery and recycling of PFAS from used products, the circular economy minimizes the environmental impact of discarded PFAS-containing items. This approach also mitigates the risk of PFAS entering landfills or being incinerated, thereby averting potential secondary environmental contamination [60].

Exploration of New Applications for Recycled PFAS: Encouraging the exploration of new applications for recycled PFAS, the circular economy stimulates market demand. This economic model creates a viable demand for recycled PFAS, rendering the recycling process more economically feasible. This transition towards a circular approach in PFAS management not only addresses environmental concerns but also establishes a foundation for sustainable economic practices in the domain of PFAS remediation [61].

Regenerative Natural Systems: The circular economy principle of regenerating natural systems aligns with the goal of avoiding the use of non-renewable resources and preserving or enhancing renewable ones, which can contribute to reducing the demand for PFAS and other non-renewable substances [62].

Sludge Management: Within the urban water cycle, the circular economy can help reduce the problems associated with PFAS in sludge, thereby minimizing the environmental impact of these substances [63].

These integrated strategies collectively position the circular economy, integrated with BAT, as a promising and comprehensive strategy for effectively addressing PFAS challenges in wastewater and the environment.

5. FOREVER CHEMICALS REMOVAL FROM WATER AND WASTEWATER

Addressing the removal of per- and polyfluoroalkyl substances (PFAS) from wastewater is imperative due to its potential consequences for future generations. Successful PFAS removal within wastewater treatment plants relies upon diverse factors, encompassing operational considerations, specific parameters of the wastewater treatment process, and the nature of the wastewater source [64]. An economically viable, environmentally sustainable, and operationally uncomplicated solution for PFAS removal from wastewater lies in the implementation of biological methods [49]. Additionally, an innovative approach involves harnessing naturally occurring microbial degradation pathways, presenting a promising methodology for the comprehensive elimination of PFAS contamination [65].

Long-chain per- and polyfluoroalkyl substances (PFAS) exhibit greater bioaccumulation and persistence, coupled with increased toxicity compared to their shorter-chain counterparts, owing to their stronger affinity for proteins and other biological molecules. Degradation of long-chain PFAS can lead to the formation of shorter-chain PFAS through various mechanisms, including biodegradation, abiotic degradation (facilitated by factors like sunlight and ozone), and advanced oxidation processes (AOPs) in water treatment. Although these processes may produce shorter-chain PFAS as intermediates, their effectiveness varies, with AOPs being efficient but costly and energy-intensive [54, 66, 67].

Conventional wastewater treatment methods often fall short of eliminating PFAS effectively, leading to the discharge of undegraded PFAS into the environment. It is crucial to acknowledge that the produced shorter-chain PFAS intermediates may retain toxicity levels similar to or even exceeding those of the original long-chain PFAS, emphasizing the importance of comprehensive removal strategies for both long-chain and shorter-chain PFAS in wastewater [67, 68]. Currently, researchers are exploring new and clean PFAS removal technologies, aiming to eliminate PFAS effectively instead of merely capturing and storing them. The recent technologies for PFAS removal from contaminated water and wastewater are as follows:

5.1. Adsorption

5.1.1. Activated carbon

The removal of per- and polyfluoroalkyl substances (PFAS) from water and wastewater is a critical environmental concern due to their persistence and potential health risks. Activated carbon has been widely utilized as an effective method for PFAS removal, although it has limitations in terms of efficiency for short-chain PFAS compounds and energy-intensive regeneration processes [62]. In recent years, researchers have conducted several experimental trials using granular activated carbon (GAC) to examine the effects of different PFAS attributes, such as isomer structure, functional groups, and perfluorocarbon chain length, on the elimination of various PFAS compounds [69, 70]. The findings indicate that GAC demonstrated removal efficiencies averaging between approximately 80% and 90% for PFAS [71, 72].

Cantoni et al. investigated PFAS adsorption in tap water using various activated carbon types, validated by full-scale plant data. Results showed AC's removal efficiency varied with surface charge, pore size, and competition with dissolved organic matter. Findings were confirmed at full scale, revealing removal variations among PFAS compounds [73]. Park et al. explored PFAS breakthrough in groundwater's using fixed-bed adsorbers and RSSCTs with four activated carbons. Results showed that PFAS breakthrough was influenced by compound hydrophobicity and carbon characteristics [8]. M.G. Kibambe et al. [74] examined the effectiveness of wastewater treatment processes for reducing perfluoroalkyl substances (PFASs), with a particular emphasis on perfluorooctane sulfonate (PFOS) removal via adsorption. Their research assessed the efficiency of various treatment methods, with a specific focus on adsorption as a key PFOS removal process. The findings underscored the potential of adsorption as a highly effective method for PFOS reduction, showcasing its ability to selectively capture and remove PFOS from wastewater, thereby offering a promising solution for mitigating PFAS contamination [74]. Riegel et al. [75] explored removing short-chain PFAS during drinking water treatment using activated carbon and ion exchange. Short-chain PFAS were effectively removed by activated carbon over short run times, while longer PFAS required longer

durations [75]. In a water utility, Burkhardt et al. conducted pilot research in two phases: first analyzing nine PFAS compounds, then sixteen. Both phases utilized five different GACs, employing pore and surface diffusion models to predict outcomes [76]. The study showed GAC effectively removed all tested PFAS. However, remediation effectiveness varied significantly between the phases, conducted at different times of the year, indicating fluctuating PFAS adsorption properties. Granular activated carbon (GAC) proved to be an efficient remediation method for PFAS removal in this pilot study, meeting the utility's treatment objectives [76].

5.1.2. Biochar

Biochar, a carbonaceous material derived from the thermal decomposition of biomass through pyrolysis, has emerged as a promising avenue for addressing the contamination of water and wastewater by polyfluoroalkyl substances (PFAS) [77]. Its efficiency in PFAS removal stems from its unique physical, chemical, and biological properties, which are influenced by the composition of the original biomass used in its production. These properties include surface area, porosity, pH, functional groups, and surface charge, all of which play pivotal roles in the adsorption and degradation mechanisms involved in PFAS removal. The diverse nature of biochar, owing to variations in feedstock and pyrolysis conditions, poses a challenge in defining it by a single characteristic. However, this diversity also offers opportunities for tailored biochar formulations optimized for specific PFAS removal applications, thus contributing to the advancement of sustainable and effective wastewater treatment technologies [78, 79].

Wu et al. [80] tested the adsorption of perfluorooctanoic acid (PFO) by engineered biochar made from three different feedstocks: switchgrass [29], water oaks leaves (WO), and biosolid (BS). The adsorption mechanisms, thermodynamic analysis, and the impact of factors such as pH, salinity, and organic matter were investigated. The biochar was engineered with additives of FeCl_3 and carbon nanotube (CNTs) to enhance PFOA adsorption, with biosolid biochar demonstrating better PFOA adsorption due to its higher contents of O% and S% as well as higher metal contents such as Ca, Cu, and Fe. Among the engineered biochars investigated, BS-Fe displayed the highest maximum adsorption capacity for PFOA at 469.65 $\mu\text{mol/g}$, while WO-CNT exhibited the lowest adsorption potential with 39.54 $\mu\text{mol/g}$. The sorption behavior of PFAS with chain lengths ranging from 4 to 11 fluorinated carbons was investigated by Fabregat-Palau et al. [81] across various carbon-rich materials, such as biochars, compost, charcoal fines, and activated carbon. The study revealed a correlation between an increase in sorption and the length of the PFAS chain, highlighting the significance of hydrophobic interactions as the primary driving force behind PFAS sorption. Emphasis was placed on the crucial role of the CORG/O molar ratio and the specific surface area (SSA) of the material as key properties influencing this sorption process. Furthermore, the research underscored the potential of biochars as an environmentally sustainable alternative to activated carbon for PFAS removal, demonstrating promising results in terms of sorption efficiency. Militao et al. [82] examined the efficiency of alginate-encapsulated plant albumin and rice straw-derived biochar in removing PFAS from water. Their study demonstrated high removal efficiency, with up to 99% for PFOS and 39% for PFBS. Particularly, the non-thermal (NT) biochar variant outperformed prior natural material-based adsorbents. The research emphasized the pH-independent nature of biochar-alginate beads and their resilience to natural organic matter.

5.1.3. Ion Exchange Resin

Ion exchange resins have been widely used for the removal of per- and polyfluoroalkyl substances (PFAS) from wastewater. These resins, including cationic exchange resins [46] and anion exchange resins, have shown effectiveness in removing positively charged contaminants and negatively charged PFAS from water sources [83]. The use of ion exchange resins for PFAS removal involves a regeneration process using an organic solvent and brine solution to treat the resin and remove PFOS and PFOA from the water [84]. Anion exchange resins, in particular, have been highlighted in various studies for their efficacy in PFAS removal, with some studies providing estimated cost curves for their implementation [85]. Adsorption using ion exchange resins has demonstrated significant promise, achieving removal efficiencies of $\geq 99\%$ for PFAS as well as dissolved organics ($>90\%$) [86, 87]. However, it's important to note that results obtained at high initial concentrations (5–1000 mg/L) of PFAS in synthetic and spiked wastewaters may not directly translate to lower and more realistic concentrations (<1000 ng/L). Additionally, the documented formation of nitrosamine precursors during the regeneration of amine-based anion exchange (IX) resins poses a notable concern [88]. Deng et al. evaluated different anion exchange resins for the removal of perfluorooctane sulfonate (PFOS) from simulated wastewater, providing insights into the sorption behavior and mechanism of PFOS on these resins [89]. Woodard et al. studied the use of ion exchange resin for PFAS removal, showing consistent results between virgin and regenerated resin loading cycles [84]. Zeidabadi et al. proposed an integrated approach combining ion exchange and electrochemical technologies for managing PFAS exhausted ion-exchange resins, showing enhanced regeneration efficacy with the presence of methanol but reduced electrochemical decomposition of PFAS [90]. Further research is needed to optimize the use of ion exchange resins for the removal of per- and polyfluoroalkyl substances (PFAS) and other pollutants to improve water treatment processes [91].

5.2. Membrane Technologies

High-pressure membrane processes such as reverse osmosis (RO) and Nanofiltration (NF) membranes are most effective for removing various classes of trace organic compounds from water [92]. Several studies have investigated the efficiency of membrane technologies for PFAS removal from water and wastewater, demonstrating significant variation based on the type of membrane used and the specific PFAS compounds targeted. Tang et al. [93] found that reverse osmosis (RO) membranes achieved over 99% removal of long-chain PFAS like PFOA and PFOS, although short-chain PFAS were less effectively removed. Similarly, Steinle-Darling and Reinhard [94] showed that RO membranes could remove over 90% of PFOA and PFOS, but highlighted that membrane fouling could affect performance. Nanofiltration (NF) membranes have also shown promise; in a study by Thompson et al. [95], NF membranes achieved 95% removal of long-chain PFAS but had reduced efficiency for shorter chains. A study by Guo et al. [96] also confirmed these findings, noting that NF membranes effectively removed PFOS with a rejection rate exceeding 90%. Forward osmosis (FO) has been explored as well, with Boo et al. [97] reporting that FO membranes could reject up to 98% of PFAS, though performance was influenced by membrane orientation and draw solution composition. Additionally, ultrafiltration (UF) combined with activated carbon adsorption was shown by Rahman et al. [11] to enhance PFAS removal, particularly for long-chain compounds, though UF alone was insufficient. Schäfer et al. [98] further corroborated these findings, showing that combined membrane

systems could achieve over 99% removal for some PFAS, but emphasized the need for hybrid approaches to address short-chain variants effectively. These studies collectively suggest that membrane technologies, particularly RO and NF, are highly effective for removing long-chain PFAS. However, very little data are available regarding the use of membranes in the removal of short-chain PFAS [99, 100]. Generally, nanofiltration (NF) membranes demonstrate high rejection rates—often exceeding 95%—for molecules with molecular weights greater than 150 Da, which includes many short-chain PFAS [101]. Research by Zeng et al. [102] indicated that lowering the pH enhances the membrane's ability to reject short-chain PFAS, underscoring the significance of pH in the rejection process. Additionally, the ionic strength can influence the extent of Donnan exclusion, affecting how membranes reject negatively charged PFAS. Organic fouling, which forms a layer on the membrane surface, also impacts PFAS rejection efficiency. Like ion exchange methods, membrane technologies do not destroy PFAS but instead produce a concentrated brine solution that requires further treatment or disposal. [103].

5.3. Electrochemical Degradation

Electrochemical degradation has shown significant potential for PFAS removal from water and wastewater, with numerous studies assessing its effectiveness. Zhuo et al. [104] investigated the use of boron-doped diamond (BDD) electrodes for degrading PFOA, achieving over 95% removal within 2 hours, demonstrating the efficiency of BDD electrodes for long-chain PFAS. Shi et al. [105] utilized Ti/Pt electrodes to target PFOS, achieving over 85% removal within 3 hours, showing the method's effectiveness for shorter-chain PFAS. Niu et al. [106] explored PbO₂ electrodes and reported up to 90% removal of both PFOA and PFOS, with PFOA being more readily removed. Singh et al. [107] used Ti/IrO₂ electrodes and achieved up to 95% removal of PFOS, indicating the potential of these electrodes in wastewater treatment. Yu et al. [108] demonstrated that Fe/N co-doped graphene-modified cathodes in an electro-Fenton process achieved over 90% PFOA removal. The enhanced degradation was due to increased hydroxyl radical production, showing the effectiveness of electrode modification in PFAS treatment.

Further research by Yang et al. [109] employed electrochemical advanced oxidation processes (EAOPs) with stainless steel anodes, achieving approximately 80% removal of PFOS and PFOA, and highlighting the need for process optimization. Adeniji et al. [110] achieved up to 90% removal of PFOA using diamond-like carbon (DLC) electrodes, reflecting their potential for PFAS treatment. Jean et al. [111] combined electrochemical oxidation with UV irradiation, achieving over 95% removal of both PFOS and PFOA, suggesting that integrating methods can enhance treatment efficiency. Pillai et al. [112] used Ti/RuO₂ electrodes and achieved up to 89% removal of PFOS, supporting the effectiveness of metal oxide electrodes. Liwara et al. [113] explored the use of palladium on carbon (Pd/C) catalysts, achieving up to 85% removal of short-chain PFAS, highlighting the potential of catalytic electrochemical processes. Additional research by Zhang et al. [114] focused on copper electrodes for PFAS removal, reporting up to 87% removal of PFOS. Yang et al. [115] evaluated nickel-based electrodes and achieved around 82% removal of PFOA, demonstrating another effective approach for PFAS degradation. Collectively, these studies illustrate the diverse effectiveness of electrochemical methods in degrading PFAS, though optimization of electrode materials and treatment conditions remains crucial.

5.4. Biodegradation and Biological Methods

Biodegradation and biological methods have emerged as promising approaches for the removal of PFAS from wastewater. These methods leverage microbial and enzymatic processes to degrade PFAS compounds, offering potential advantages in terms of cost-effectiveness and environmental sustainability. One of the key studies in this area is by Xu et al. [116], examined how PFOA and PFOS affect soil microbial communities, finding that these contaminants significantly reduce microbial diversity and disrupt key soil processes. Higher concentrations of PFOA and PFOS caused greater changes, highlighting the need for careful monitoring of PFAS in soil. Similarly, Smith et al. [117] review innovative treatment technologies for PFAS-contaminated water, specifically foam partitioning and electrochemical methods. Foam partitioning achieved up to 95% removal of PFAS from water, while electrochemical techniques demonstrated up to 90% degradation of PFAS. The study highlights these methods' effectiveness and potential for improving PFAS remediation. A more recent study by Torres-Farradá et al. [118] investigated the potential of white-rot fungi, specifically focusing on the enzyme laccase, for the degradation of per- and polyfluoroalkyl substances (PFAS), particularly PFOA and PFOS. Their study demonstrated that laccase could effectively degrade these compounds, achieving removal rates of 75% for PFOA and 70% for PFOS over a period of 15 days. This research highlights the promise of using fungal enzymes in bioremediation efforts to address the environmental challenges posed by persistent pollutants like PFAS. Tow et al. [119] evaluated the performance of a hybrid biological and chemical treatment system, combining microbial degradation with advanced oxidation processes, which resulted in up to 90% removal of PFOA.

The potential of using engineered bacteria was highlighted by Berhanu et al. [120] who developed a recombinant *E. coli* strain engineered to express PFAS-degrading enzymes. This genetically modified strain was able to degrade 85% of PFOS within 7 days, demonstrating the potential of genetic engineering to enhance the biodegradation of PFAS. By introducing specific genes encoding PFAS-degrading enzymes into *E. coli*, the researchers were able to significantly improve the degradation rate compared to unmodified bacteria. Shahsavari et al. [121] investigated the use of activated sludge systems for PFAS removal, achieving up to 70% reduction in PFOS concentrations through optimized microbial activity.

In another study, Grgas et al. [122] examined the use of anaerobic digestion processes for PFAS removal. They reported up to 60% reduction of PFOA and PFOS through the application of specialized anaerobic bacteria. Similarly, Smith et al. [123] explored biological methods for PFAS removal in wastewater treatment, demonstrating that certain microbial communities could degrade up to 70% of specific PFAS compounds under optimized conditions. The study highlighted the integration of these biological processes into existing wastewater treatment plants, suggesting that coupling them with foam partitioning techniques could enhance overall PFAS removal efficiency. These findings indicate the potential for biologically based strategies to contribute to more sustainable PFAS remediation efforts. Further research by Zhou et al. [124] reviewed the biodegradation of PFAS, revealing that while complete mineralization is challenging, specific microbial strains can partially degrade shorter-chain PFAS compounds. The review emphasizes that although biodegradation alone may not achieve full PFAS removal, integrating these biological processes with other treatment technologies could significantly enhance overall remediation efficiency in wastewater systems. Bacteria such as *Pseudomonas aeruginosa* have also been studied extensively. For instance,

Chetverikov et al. [125] examined the biodegradation potential of C₇-C₁₀ perfluorocarboxylic acids by a new strain of *Pseudomonas mosselii*. The study demonstrated that this strain could degrade up to 60% of these PFAS compounds under optimal conditions. The genomic analysis revealed specific enzymes responsible for breaking down the carbon-fluorine bonds, offering insights into the mechanisms of PFAS biodegradation. These findings suggest that *Pseudomonas mosselii* could be a promising candidate for biological PFAS remediation in wastewater treatment. Collectively, these studies underscore the effectiveness of various biological and biodegradation methods for PFAS removal, though further research is needed to optimize these processes and address challenges such as degradation of short-chain PFAS and overall treatment efficiency.

4. CONCLUSIONS

The pervasive environmental and health risks posed by per- and polyfluoroalkyl substances (PFAS) demand an urgent and comprehensive response. The persistence of these synthetic chemicals, coupled with their widespread use, has resulted in significant contamination, particularly in aquatic environments. The technological advancements reviewed in this study—electrochemical degradation, nanofiltration, adsorption, and biodegradation—offer promising avenues for PFAS mitigation. However, the complexity and cost of these methods often limit their practical application, and none can yet be considered a panacea. The most effective long-term strategy lies in the prevention of PFAS emissions at their source. This requires stringent regulatory controls on the production and use of PFAS, alongside robust efforts to develop and commercialize non-toxic alternatives. Such preventive measures not only reduce the burden on treatment technologies but also align with the principles of a circular economy, where resource efficiency and waste minimization are prioritized.

Transitioning to a circular economy is particularly pertinent, as it presents a systemic approach to reducing environmental contaminants, including PFAS. However, this transition is far from straightforward. It necessitates coordinated action across multiple sectors, including policy reform, industrial innovation, and shifts in consumer behavior. The global nature of PFAS contamination also calls for international collaboration, as unilateral actions are insufficient to address a problem of this magnitude. Collaborative efforts between regulatory agencies, industries, academic researchers, and the public are essential. Regulatory frameworks must evolve in response to new scientific findings, and industries must be held accountable for environmental stewardship. Public engagement and education are critical in driving demand for safer products and supporting policy initiatives aimed at reducing PFAS exposure. Ongoing research is vital to further elucidate the behavior and impact of PFAS in the environment. The development of more sustainable, cost-effective treatment technologies is imperative, as is the investigation of natural attenuation processes and the potential for microbial degradation of PFAS. Future studies should focus on understanding the long-term environmental and health impacts of PFAS, particularly as they relate to cumulative exposure and low-dose effects.

In conclusion, a multifaceted approach that integrates prevention, advanced treatment technologies, regulatory oversight, and public awareness offers the most viable pathway to mitigating the impact of these persistent pollutants. The goal of a toxic-free environment, though ambitious, is achievable with sustained

effort and international cooperation, ensuring the protection of both human health and the natural world for future generations.

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Declaration of research and publication ethics

The authors of the paper declare that we followed the scientific, ethical and citation rules of Environmental Toxicology and Ecology in all processes of the paper and that we did not make any falsification of the data collected. Furthermore, we declare that ETOXEC and its Editorial Board are not responsible for any ethical violations that may have occurred and that this study has not been evaluated in any other academic publication environment than ETOXEC.

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