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Industrial Process Optimization for the Effective Removal of Per- and Polyfluoroalkyl Substances (PFAS) from Water Treatment Systems

Mohammad Fokhrul Islam Buian[1], Nafis Ahmed Pantho[2*], Iqtiar Md Siddique[3], Anamika Ahmed Siddique[3]

[1]Department of Mechanical Engineering, Lamar University, US
[2]Department of Civil Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh.
[3]Department of Mechanical & Aerospace Engineering, University of Texas at El Paso, US
*mbuian@lamar.edu
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ABSTRACT

Per- and Polyfluoroalkyl Substances (PFAS) contamination in water sources has emerged as a significant environmental and public health concern. PFAS, known for their persistent and bio accumulative nature, has been widely detected in drinking water supplies, surface waters, and groundwater. This abstract provides a concise summary of the current state of PFAS contamination, emphasizing the need for effective treatment methods. Various treatment technologies have been explored in drinking water and wastewater treatment plants to mitigate PFAS concentrations. Advanced methods such as activated carbon adsorption, membrane processes (reverse osmosis and nanofiltration), and ongoing research into biodegradation mechanisms have shown promise in addressing the challenges posed by PFAS. The abstract underscores the importance of continued research, international collaboration, and the development of robust treatment strategies to manage PFAS contamination in water sources and safeguard water quality.

Key words: Industrial Process, Optimization, PFAS, Water Treatment

INTRODUCTION

Per- and Polyfluoroalkyl Substances (PFAS), comprising synthetic chemicals recognized for their fluorinated carbon chains, possess distinctive attributes such as oil and water repellency, thermal stability, and resistance to chemical breakdown (Buck et al., 2011). PFAS, represented by compounds like perfluorooctanoic acid (PFOA), have been historically employed in industrial processes and consumer products like Teflon, non-stick cookware, water-resistant textiles, and firefighting foams (Arinaitwe et al., 2021; Dhara & Fayshal, 2024; Ye et al., 2015). This widespread use has, however, raised significant environmental and health fears. Due to their strong carbon-fluorine bonds, PFAS persist in the environment, accumulating in soil, water, and air, thereby posing potential health risks like developmental effects, liver damage, immune system suppression, and an increased risk of certain cancers (Barisci et al., 2021; Changet al., 2022; Grønnestad et al., 2019; Stoiberet al., 2020). The global response to these concerns includes ongoing research that emphasizes understanding the environmental fate and health implications of PFAS exposure. The environmental and health concerns associated with PFAS contamination in water have attracted scientific scrutiny, revealing the ubiquity of PFAS due to historical usage (Khalekuzzaman et al., 2023). Kamal et. al (2019) gives practical evidence by using RFID technology for warehouse management by android application which has great impact water treatment system as we have plan to adopt this technology for further research. Parvez et. al (2022) gives a Great discussion on ergonomics factor in his two different research paper of students from which we consider the human working posture for the efficiency measurement of worker in the WTP System because ergonomics factors are one of the most crucial matters for setting and testing of different chemical materials. Ullah et al. (2023) describes very gently in his three different papers regarding manufacturing excellence, scheduling operation and equipment efficiency from which we can consider for the industrial process optimization work by reducing wastage in the water treatment system. Shakil et. al (2013) interprets the process flow chart for a jute mill which is very informative for our research though this field is different, but we have analyzed that process flow is very helpful for any types of measurement and analysis work and we have plan for process optimization work in water treatment system. Ullah et.at (2023) finds the excellent situation of a job shop production which will be helpful for wastage reduction work in industrial process optimization in the industrial water treatment system. Ullah and colleagues (2023) and (2024) eloquently present insights in four separate papers addressing manufacturing excellence, operational scheduling, and equipment efficiency. These contributions are crucial considerations for water treatment systems and their process optimization workTheir persistence in water sources poses substantial risks to ecosystems and human health, with identified contamination in water sources (Singh et al., 2020). Moreover, PFAS can be classified into different groups and subgroups based on their terminal functional groups, followed by a categorization by chain length into long and short-chain compounds, as illustrated in Figure 1.

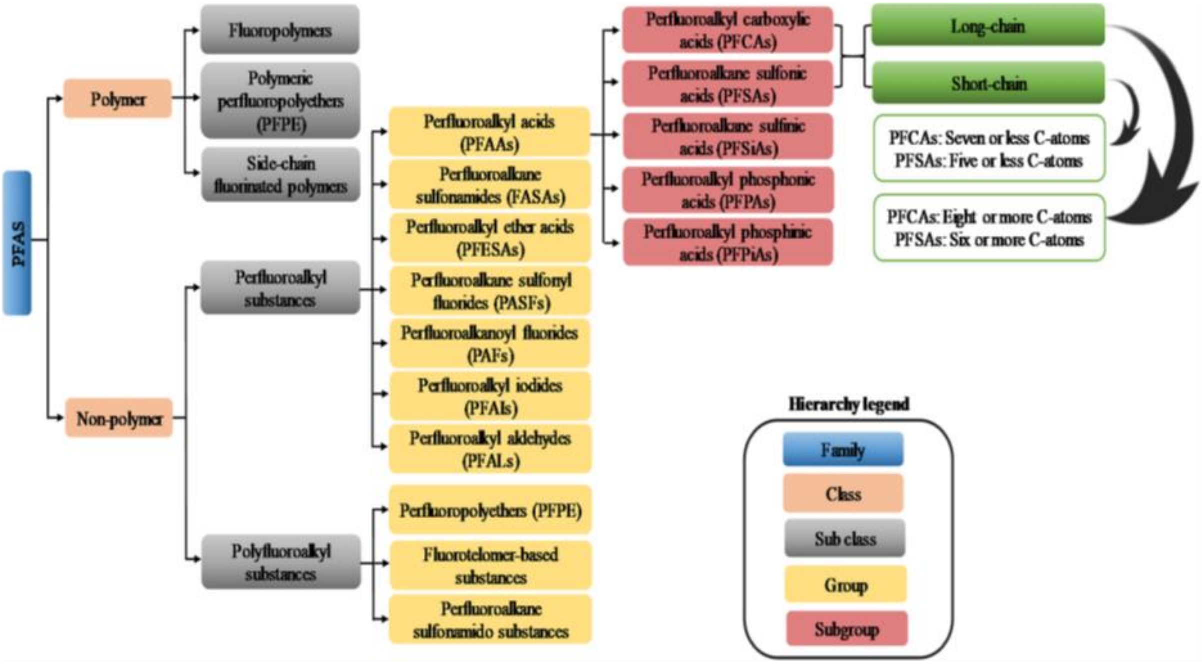

Figure 1: categorization by chain length

METHODOLOGY: PFAS OCCURRENCE IN WATER SOURCES:

Industrial Discharges

An overview of major industries contributing to PFAS contamination in water reveals a diverse range of sectors that utilize these substances in various processes. Industries involved in the production of textiles, where PFAS are used for water and stain resistance, have been identified as significant contributors to PFAS in water sources. The manufacturing of non-stick cookware, utilizing PFAS for its unique properties, is another major industry implicated in PFAS contamination (Khalekuzzaman et al., 2024). Additionally, industries utilizing aqueous film-forming foams (AFFFs) containing PFAS for firefighting purposes, including both training areas and active firefighting sites such as airports, contribute to the release of PFAS into water bodies (Uddin et al., 2022; Uddin et al., 2023). Semiconductor manufacturing facilities, which use PFAS in certain processes, have also been recognized as sources of PFAS contamination in water (Fayshal et al., 2023). These diverse industrial activities underscore the need for comprehensive regulatory measures and monitoring programs to address and mitigate PFAS pollution in water.

Firefighting Foam Usage

The utilization of firefighting foam has been a significant contributor to PFAS contamination in water, with discernible impacts on PFAS levels. Aqueous film-forming foams (AFFFs), commonly used in firefighting activities, contain PFAS to enhance their effectiveness in suppressing flammable liquid fires. The application of AFFFs during firefighting exercises and actual incidents has led to the release of PFAS into the environment, particularly into water sources (Kim et al., 2-15).

Several case studies and incidents underscore the environmental impact of firefighting foam contamination, revealing elevated PFAS levels in water and the widespread consequences of aqueous film-forming foam (AFFF) usage (Chen et al., 2017). Military bases, airports, and firefighting training areas have been focal points of contamination. Notable cases include the contamination of drinking water near military bases, such as at Camp Lejeune in the United States, where PFAS from AFFF use has been linked to adverse health effects among residents. Incidents at airports, like those near facilities using AFFF for firefighting purposes, have resulted in PFAS contamination of groundwater and surface water (Fayshal et al., 2024). The 2018 incident at Sydney Airport in Australia is an illustrative example. Moreover, firefighting training areas, where AFFF is routinely used, have been associated with persistent PFAS contamination in water bodies. These cases emphasize the urgency of addressing the environmental and health implications of firefighting foam contamination (Kunacheva et al., 2012). Figure 2 presents the chemical structure of PFOA and PFOS. This ubiquity is attributed to historical and ongoing industrial activities, as well as the widespread use of consumer products containing PFAS.

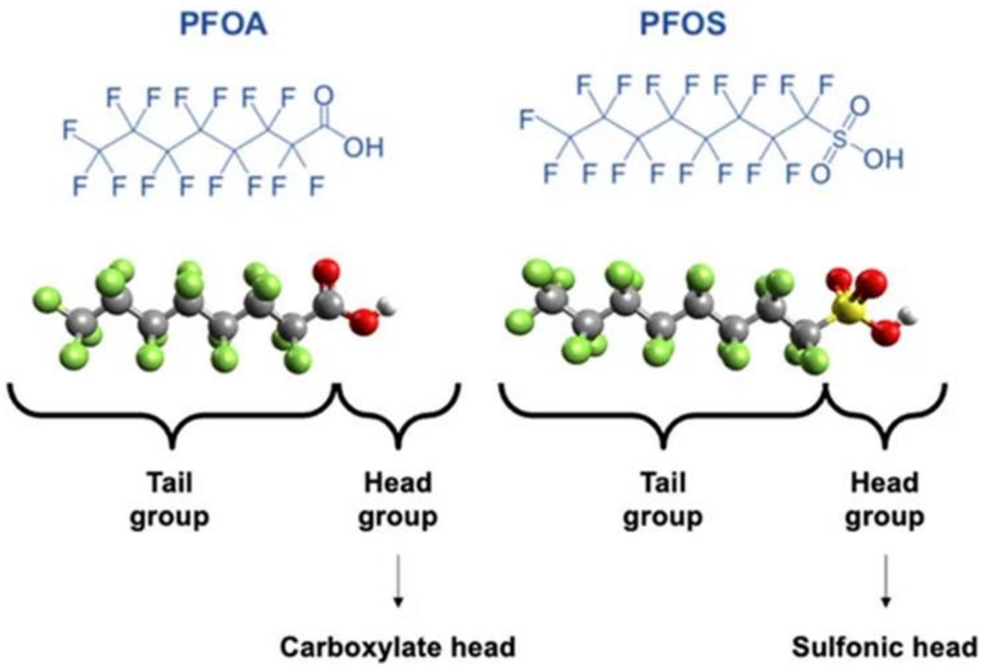

Figure 2: Biochemical structure of PFOA and PFOS. Adapted from Meegoda et al., (2022)

Consumer Product Leaching:

Consumer product leaching is a significant pathway through which PFAS enter water sources, contributing to environmental contamination. PFAS, widely used in consumer goods for their water and stain-resistant properties, can leach into water. Moreover, this leaching occurs over time, particularly when products degrade or come into contact with water during everyday use. Common sources of PFAS in consumer goods include waterproof clothing, carpets, and food packaging materials treated with PFAS. The leaching of PFAS from these items into water systems has been documented, raising concerns about the potential health and environmental impacts (Deng et al., 2023).

PFAS IN DRINKING WATER TREATMENT PLANTS:

Detection and Monitoring:

The detection and monitoring of PFAS in raw water involve employing various analytical techniques to assess the presence and concentration of these substances. Common methods include liquid chromatography-mass spectrometry (LC-MS) and gas chromatography-mass spectrometry (GC-MS), which enable the identification and quantification of specific PFAS compounds in water samples (Kucharzyk et al., 2017). Additionally, techniques like solid-phase extraction and high-performance liquid chromatography (HPLC) are utilized to isolate and analyze PFAS. The complexity of PFAS mixtures requires sophisticated instrumentation to ensure accurate detection (DeLuca et al., 2022). Regarding the frequency of detection in drinking water sources, studies globally have reported widespread contamination. PFAS have been detected in drinking water supplies near industrial facilities, military bases, and areas with historical firefighting foam usage (Gaber et al., 2023; Clara et al., 2009). The frequency of detection varies depending on geographical locations and the proximity of potential contamination sources. Rigorous monitoring programs are essential to track PFAS levels in raw water and drinking water sources, ensuring timely identification and mitigation of potential risks.

Challenges in Traditional Treatment:

The examination of limitations in conventional drinking water treatment processes reveals challenges in effectively removing Per- and Polyfluoroalkyl Substances (PFAS) due to their unique physicochemical properties. Traditional treatment methods such as coagulation, flocculation, sedimentation, and conventional filtration encounter difficulties in efficiently eliminating PFAS from water. The persistence of PFAS is attributed to their stable carbon-fluorine bonds, which resist degradation during these processes (Hepburn et al., 2019). Coagulation and flocculation, which usually target the removal of particulate matter, are less effective in capturing dissolved PFAS. Similarly, sedimentation and conventional filtration may not achieve substantial PFAS removal due to the small size and stable nature of these compounds. The challenges in traditional treatment processes underscore the need for innovative approaches and advanced technologies to address the persistence of PFAS in drinking water.

Advanced Treatment Technologies

Activated carbon filtration is a prominent advanced treatment method employed for PFAS removal, leveraging the adsorption capabilities of activated carbon to capture these persistent substances. The mechanism involves the attraction of PFAS molecules to the activated carbon surface, resulting in their removal from water. The effectiveness of this process is influenced by several key factors:

Adsorption Capacity: Activated carbon possesses a high surface area with a multitude of pores and a complex structure. This high surface area provides ample sites for PFAS molecules to adhere, resulting in effective removal.

Chemical Affinity: The activated carbon surface has a strong chemical affinity for PFAS compounds. The carbon-fluorine (C-F) bonds in PFAS have a particular attraction to the carbon surface, facilitating effective adsorption.

Pore Size Distribution: The diverse pore size distribution in activated carbon allows it to capture a broad range of PFAS molecules, including both short-chain and long-chain compounds. This versatility enhances its effectiveness in PFAS removal (Inyang et al., 2017).

Contact Time: The duration of contact between water and activated carbon is crucial for efficient adsorption. Longer contact times provide more opportunities for PFAS molecules to interact with the activated carbon surface.

Water Chemistry: The pH and presence of other co-existing contaminants in water can influence the effectiveness of activated carbon filtration. Optimal conditions are often maintained to maximize PFAS removal.

Activated carbon filtration has demonstrated high effectiveness in removing various PFAS compounds, including perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS). Studies have shown removal efficiencies exceeding 90%, making it a reliable technology for PFAS mitigation (Jiawei et al., 2019). However, it is important to note that the performance may vary depending on the specific activated carbon properties, water quality, and the characteristics of PFAS present. Membrane filtration, encompassing technologies such as reverse osmosis (RO) and nanofiltration (NF), is a versatile and effective method for the removal of Per- and Polyfluoroalkyl Substances (PFAS) from water. These membrane-based processes operate on the principle of selectively allowing water molecules to pass through while blocking the passage of contaminants, including PFAS (Joshi et al., 2013). Here are detailed discussions on the applications and removal efficiency of reverse osmosis and nanofiltration:

Reverse Osmosis (RO)

Applications:

Drinking Water Treatment: RO is commonly used for the purification of drinking water, especially in areas facing contamination challenges such as PFAS.

Industrial Wastewater Treatment: RO is applied in industrial settings to treat wastewater, removing PFAS and other pollutants.

Groundwater Remediation: RO plays a role in the remediation of groundwater contaminated with PFAS, offering a robust treatment solution.

Removal Efficiency:

RO membranes have a tight pore structure, effectively blocking the passage of PFAS molecules.

Removal efficiency for PFAS is typically high, exceeding 90%, making it a reliable method for reducing PFAS concentrations in treated water.

The efficiency can vary based on the specific membrane properties, water chemistry, and PFAS characteristics.

Nanofiltration (NF):

Applications:

Drinking Water Treatment: NF is used for the removal of PFAS in drinking water treatment plants.

Wastewater Treatment: NF is applied in the treatment of industrial and municipal wastewater to reduce PFAS levels.

Desalination: NF is employed in desalination processes, and its selectivity can aid in PFAS removal.

Removal Efficiency:

NF membranes have a larger pore size compared to RO, allowing for the selective removal of certain ions and molecules, including PFAS.

Removal efficiency for PFAS is generally high, with reported rates exceeding 90%.

The specific membrane characteristics, operating conditions, and water quality parameters influence the removal efficiency.

Regulatory Framework

The regulatory landscape for Per- and Polyfluoroalkyl Substances (PFAS) in drinking water is evolving globally, with various regions establishing standards and guidelines to address the potential health risks associated with PFAS exposure. Rahman & Shohan (2015) interpret how supplier selection may have impact for water treatment system equipment purchase work. Rahman et. al & Siddique et al. (2023) considers the cryptocurrency system which is the most important factor for any sector for choosing mapping and materials for smooth operation running that can be applied to our treatment system energy saving. Molla et al. (2023) & (2024) underscore the importance of medical textiles with plantable and implantable options, serving as a focal point for future environment related research in water treatment systems. Mustaquim (2024) applies in two different papers regarding the remote sensing methods in land surface interpretation, contributing to the arrangement of good contribution for the water treatment process optimization work. Noman at el. (2020) done a good project on data retrieval approach in his two different paper and we will consider as we have a future for in the future. Hasan et al. (2017) describes solar cap energy production system and we have used this technology for our treatment plant wastage reduction plan.

Overview of Existing Regulations and Guidelines

United States: The U.S. Environmental Protection Agency (EPA) has set a non-enforceable Health Advisory Level of 70 parts per trillion (ppt) for the combined concentrations of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in drinking water (Lenka et al., 2022; Mizan et al., 2023). Several U.S. states have also implemented their own regulatory standards.

European Union: The European Union (EU) is in the process of evaluating and establishing regulations for PFAS in drinking water. The European Chemicals Agency (ECHA) has identified PFAS as substances of concern, and discussions on regulatory limits are ongoing (Clara et al., 2009).

Australia: In Australia, there is no national standard for PFAS in drinking water. However, individual states and territories have implemented their own guidelines and limits (Mailler et al., 2015). For instance, the state of Queensland has set a guideline value for PFOS and PFOA in drinking water.

Comparison of Standards Across Different Regions:

Threshold Levels: The threshold levels for PFAS in drinking water vary significantly among regions. While the U.S. EPA Health Advisory Level is set at 70 ppt for PFOA and PFOS combined, other countries may have different threshold values. For instance, some European countries are considering more stringent limits.

Inclusion of Additional PFAS Compounds: Regulatory frameworks also differ in terms of the specific PFAS compounds included (Wanninayake et al., 2021). Some regulations focus on PFOA and PFOS, while others consider a broader range of PFAS compounds.

Monitoring Requirements: The frequency and methodology for monitoring PFAS in drinking water can vary. Some regulations mandate regular monitoring, while others may have more flexible requirements.

Response Actions: The prescribed response actions for exceeding PFAS limits can vary, including measures such as public notification, water source treatment, or the development of remediation plans.

PFAS IN WASTEWATER TREATMENT PLANTS

Influent Characteristics

Understanding the composition and concentrations of Per- and Polyfluoroalkyl Substances (PFAS) in wastewater influents is crucial for effective wastewater treatment and environmental management. The influent characteristics of PFAS in wastewater exhibit notable variability influenced by a combination of industrial discharges and domestic sources.

Composition:

Industrial Discharges: Wastewater influents often reflect the PFAS used in industrial processes. Industries such as textile manufacturing, semiconductor production, and facilities employing firefighting foams contribute to specific PFAS compounds in wastewater. For example, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) may be prevalent in influents from industrial discharges.

Domestic Sources: PFAS from everyday consumer products, such as non-stick cookware, waterproof textiles, and food packaging, enter wastewater influents from domestic sources. The composition may include a diverse range of PFAS compounds with varying carbon chain lengths.

Concentrations:

Industrial Influence: Wastewater influents from industrial discharges can exhibit higher concentrations of PFAS, depending on the types of processes and materials used. Concentrations may vary significantly based on the specific industrial activities in the catchment area.

Domestic Contributions: PFAS concentrations from domestic sources in influents are influenced by consumer behavior, product usage, and disposal practices. While individual household contributions may be lower, the cumulative effect can be substantial.

Variability:

Temporal Variations: The concentrations of PFAS in wastewater influents can exhibit temporal variations. Seasonal patterns, changes in industrial production, and fluctuations in consumer behavior can contribute to variability over time.

Spatial Variations: Spatial variations in PFAS influent characteristics may occur due to the distribution of industrial facilities and variations in residential practices across different regions within a catchment area.

Biological Treatment Challenges:

Traditional biological treatment processes face significant limitations in the removal of Per- and Polyfluoroalkyl Substances (PFAS) from wastewater, posing challenges for effective treatment. The unique physicochemical properties of PFAS compounds contribute to these challenges, impacting the efficiency of biological treatment (Vecitis et al., 2010). Additionally, the presence of PFAS can influence microbial communities in wastewater treatment systems.

Limitations of Traditional Biological Treatment

Biodegradability: PFAS compounds are characterized by stable carbon-fluorine bonds, rendering them resistant to degradation by conventional biological processes. Microorganisms typically involved in biological treatment, such as bacteria and fungi, struggle to break down these strong bonds, leading to limited biodegradability.

Slow Transformation Rates: The slow transformation rates of PFAS in biological treatment systems further hinder the effectiveness of traditional processes. The persistence of PFAS compounds extends their residence time in wastewater treatment plants, impeding overall removal efficiency.

Incomplete Mineralization: Biological treatment may result in incomplete mineralization of PFAS, leading to the formation of transformation products that can still exhibit environmental persistence and potential toxicity.

Impact on Microbial Communities

Microbial Inhibition: PFAS compounds, particularly certain long-chain variants, have been reported to exhibit inhibitory effects on microbial communities. This inhibition can disrupt the metabolic activities of microorganisms involved in biological treatment, affecting overall treatment performance.

Shifts in Microbial Diversity: Exposure to PFAS can induce shifts in microbial diversity and community structure. Certain microorganisms may adapt to the presence of PFAS, while others may be inhibited, leading to alterations in the composition of microbial communities in wastewater treatment systems.

Reduced Treatment Performance: Changes in microbial communities, coupled with the inhibitory effects of PFAS, can result in reduced treatment performance. This may manifest as lower pollutant removal efficiencies and compromised overall wastewater treatment plant functionality.

Addressing the challenges associated with PFAS in biological treatment requires innovative strategies, such as incorporating advanced treatment technologies or modifying biological processes. Ongoing research aims to understand the interactions between PFAS and microbial communities better, seeking ways to enhance biodegradation and improve the resilience of biological treatment systems.

Advanced treatment strategies play a pivotal role in addressing the challenges posed by Per- and Polyfluoroalkyl Substances (PFAS) in wastewater. Two prominent approaches include activated carbon adsorption and membrane processes.

Activated Carbon Adsorption:

Application:

Activated carbon adsorption involves the use of porous carbon materials to capture and remove PFAS from wastewater.

Granular activated carbon (GAC) and powdered activated carbon (PAC) are commonly employed in adsorption processes.

Applications include both fixed-bed adsorption columns and powdered activated carbon dosing in wastewater treatment plants.

Effectiveness:

Activated carbon is highly effective in adsorbing PFAS due to its large surface area and strong affinity for these substances.

The adsorption process is capable of removing a broad range of PFAS compounds, including perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS).

Effectiveness is influenced by factors such as contact time, activated carbon dosage, and the specific characteristics of PFAS present.

Membrane Processes in Wastewater Treatment:

Application:

Membrane processes, including reverse osmosis (RO) and nanofiltration (NF), involve the use of semi-permeable membranes to selectively separate PFAS from water.

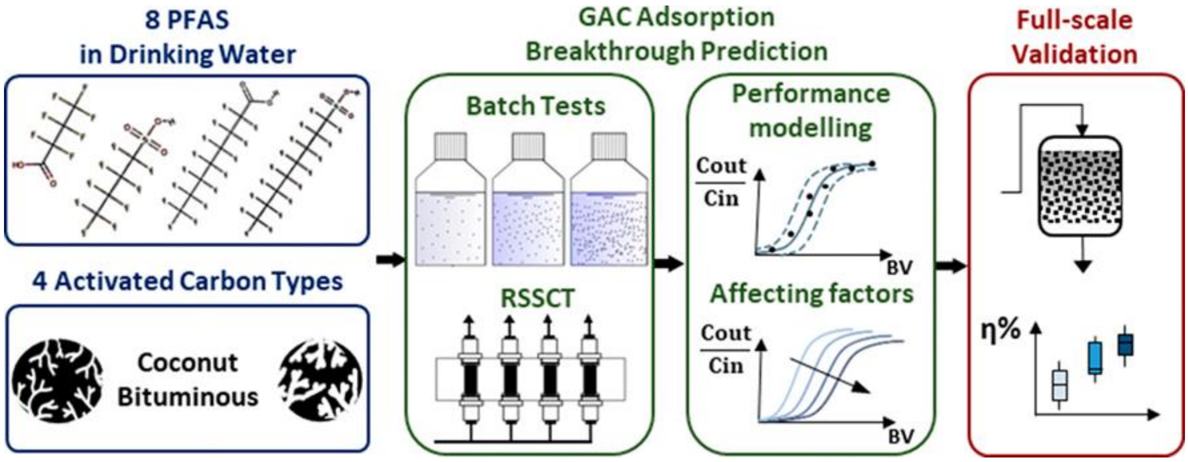

Figure 3: Effective PFAS removal in real drinking water using GAC. Adapted from Cantoni at al., (2021)

RO utilizes high pressure to force water through a membrane, while NF operates with a slightly larger pore size, allowing for selective removal of PFAS.

Membrane processes are applied at various stages in wastewater treatment plants.

Effectiveness:

RO and NF have demonstrated high removal efficiencies for PFAS, often exceeding 90%.

These processes effectively reject PFAS due to the semi-permeable nature of the membranes, blocking the passage of PFAS molecules while allowing water to permeate.

Effectiveness may be influenced by membrane properties, operating conditions, and water chemistry.

Considerations:

Activated Carbon Regeneration: Activated carbon can be regenerated for reuse through thermal reactivation processes, enhancing its sustainability.

Energy Consumption: Membrane processes, particularly RO, may require higher energy input compared to activated carbon adsorption. Optimization strategies aim to mitigate energy consumption.

In summary, activated carbon adsorption and membrane processes are advanced treatment strategies that demonstrate high effectiveness in removing PFAS from wastewater. Their application in wastewater treatment plants is influenced by factors such as efficiency, cost, and environmental considerations.

Biosolids Concerns

The presence of Per- and Polyfluoroalkyl Substances (PFAS) in biosolids, a byproduct of wastewater treatment, raises concerns due to potential accumulation and the associated risks when these biosolids are applied to agricultural land.

Accumulation of PFAS in Biosolids:

Wastewater Treatment Contribution: PFAS present in wastewater influents can accumulate in biosolids during the wastewater treatment process. The persistence of PFAS and their resistance to degradation contribute to their presence in biosolids.

Source of Biosolids Contamination: The accumulation of PFAS in biosolids is influenced by the characteristics of the influent wastewater, including the concentrations and types of PFAS compounds present. Industrial discharges and domestic sources contribute to the variability in PFAS composition in biosolids.

Risks Associated with Biosolids Application to Agricultural Land:

Soil Contamination: Biosolids containing PFAS, when applied to agricultural land as a soil amendment, can introduce these substances into the soil. PFAS may persist in the soil due to their resistance to degradation, leading to potential long-term contamination.

Plant Uptake: PFAS can be taken up by plants from the soil, leading to their presence in crops. This raises concerns about the potential transfer of PFAS from biosolids-amended soil to the food chain.

Groundwater Contamination: PFAS in biosolids may leach into groundwater, particularly in areas with sandy soils or where biosolids are applied at high rates. This poses a risk to groundwater quality and may contribute to the spread of PFAS in the environment.

Human Exposure: The application of PFAS-contaminated biosolids to agricultural land raises concerns about human exposure through the consumption of crops grown in amended soils. This exposure pathway adds to the complexity of managing PFAS risks.

Mitigation and Management:

Regulatory Measures: Regulatory frameworks may include guidelines or limits on PFAS concentrations in biosolids to minimize environmental and human health risks.

Alternative Disposal Options: Considering alternative disposal methods for biosolids, such as incineration, may be explored to reduce the potential for PFAS accumulation in agricultural soils.

Monitoring and Assessment: Rigorous monitoring of biosolids, soil, and groundwater is essential to assess the extent of PFAS contamination and inform mitigation strategies.

In summary, the concerns related to biosolids arise from the accumulation of PFAS during wastewater treatment and the associated risks when these biosolids are applied to agricultural land. Proper management practices, including regulatory measures, alternative disposal options, and thorough monitoring, are crucial for mitigating the potential environmental and human health impacts associated with PFAS in biosolids.

CONCLUSION

In conclusion, advancements in PFAS treatment have been notable, with the successful implementation of advanced technologies like activated carbon adsorption and membrane processes, coupled with the development of regulatory frameworks to address PFAS in drinking water and wastewater. However, significant knowledge gaps persist, particularly regarding the mechanisms of biodegradation, long-term fate and transport, and the health impacts of PFAS exposure. Further research is needed to optimize treatment processes, understand the complete biodegradation mechanisms, and assess the potential risks associated with biosolids application. International collaboration remains crucial for harmonizing regulatory standards and collectively addressing the global challenges posed by PFAS contamination. While progress has been made, ongoing research and collaborative efforts are imperative to comprehensively manage the environmental and public health implications of PFAS.

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