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Review of Yangtze River PFAS Treatments: A Comparison Between Activated Carbon, Reverse Osmosis, and Foam Fractionation in the Context of the Yangtze River

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Abstract. The Yangtze River is a vital source of food and water for hundreds of millions of Chinese citizens. However, recent studies have shown alarming levels of per- and polyfluoroalkyl substances (PFAS), notorious for their stability, environmental persistence, and potential toxicity to humans and wildlife, polluting the water. The presence of PFAS in the Yangtze River poses significant hazards to human health and the aquatic ecosystems, as ingestion of PFAS leads to harmful bioaccumulation. Given the river's crucial role as a water and food source, developing effective treatment strategies for PFAS is imperative. This review examines various removal methods for PFAS, including activated carbon, reverse osmosis, and foam fractionation. We will compare these technologies, assessing their treatment efficiency, reusability, and environmental impact. Notably, foam fractionation is the most promising method, achieving over 95% removal efficiency for perfluoro-octanoic acid (PFOA) and general PFAS. This method is also energy-efficient and generates minimal waste, resulting in the least detrimental environmental impacts, with very few secondary pollutants or harmful byproducts produced. Future research could investigate the optimization of solvents and catalysts, cost-effectiveness, and the feasibility of material manufacturing to enhance PFAS remediation efforts in the Yangtze River.

Keywords: Per- and Polyfluoroakyl Substances(PFAS), Perfluorooctane Sulfonic Acid(PFOA), Yangtze River, Activated Carbon, Reverse Osmosis, Foam Fractionation

1. Introduction

Discovered in its first form as polychlorotrifluoroethylene (PCTFE) by Fritz Schloffer and Otto Scherer in 1937 at a former German chemical conglomerate IG Farben, PFAS, also known as poly-fluoroalkyl substances have become widely used over the past eight decades [1]. Largely unregulated in its use until the early 21st century, the proliferation of these chemicals resulted in their existence in everything from firefighting foam and aerospace technologies to consumer products [2]. Due to its physicochemical properties, PFAS is often used in various surfactants, which repel water and oil and are heat-resistant [3]. Its adverse health and environmental effects have long

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been known(tests in the 1970s have shown that PFAS is toxic when inhaled or ingested) but have only been acknowledged recently, with the United Nations Organization of Economic Corporation and Development (OECD) releasing its hazard assessment for perfluorooctane sulfonic acid (PFOS) in 2002 [4]. Made up of a chain of linked carbon and fluorine atoms of various lengths, PFAS are synthetic compounds and persistent organic pollutants. Its inert carbon-fluorine (CF) bonds and high polarity make PFAS thermally and chemically stable, recalcitrant chemicals, able to persist in the environment for over 1000 years [5], earning it the moniker of “forever chemical” [5]. Over 97% of Americans, 98.5% of Canadians, and 99% of all humans have detectable amounts of PFAS in their bloodstream [6,2]. Current PFAS treatments include ion exchange and activated carbon as the two most commercially used options, with others like membrane filtration techniques and electrolysis available. Despite being an industrial superpower producing 31.6% of global manufacturing, China has few PFAS regulations, leading to significant pollution in rivers like the Yangtze [7,8]. Exacerbated by the construction of the Three Gorges Dams, the Yangtze River has had levels of PFAS over one order of magnitude higher than EU and EPA regulations [9,7]. Very few papers have specifically focused on comparing different forms, and even less so in specific locations, accordingly, our article will attempt to analyze different forms of PFAS treatments in the context of the Yangtze River. We continue by further explaining our treatment analyses by quantifying the PFAS situation in the Yangtze River. Then, we will present our results and their implications. Lastly, we will conclude and discuss points of interest for future studies.

2. Context

To fully grasp the significance of PFAS pollution in the Yangtze River, it is essential first to outline the river's current state and the pollution's extent. This will provide crucial context and quantify the issue, highlighting its urgency. Subsequently, we will present a brief treatment overview and detail our rationale for assessing treatment methods and why specific strategies were chosen. This structure will help clarify the problem's scope and the remediation pathways.

2.1. Quantifying the problem

PFAS has been absorbed into many aspects of the environment, from topsoil, groundwater, rivers, and oceans to even wildlife [7,4]. Notably, PFAS have even been found in polar areas, showcasing its detrimental tenacity and long-distance transportation [7]. The Yangtze River, China’s longest and most significant river, flows for more than 6300 km from the Qinghai-Tibet Plateau eastward to the East China Sea, powering a large section of China [7,8]. The Three Gorges Dam on the Yangtze River, built from 1994 to 2006, remains the largest operative dam in the world generating 22.5 gigawatts, 14% of China’s total hydropower. Additionally, the Yangtze River basin area produces over half of all the fish and two-thirds of all the rice consumed nationally. Over a third of the Chinese population rely on the river for water; the basin area accounts for over 20% of the country’s GDP. Any pollution in the Yangtze River will likely have rippling consequences. The building of numerous dams along the river has also significantly ruined the riverbed [7]. River sediment is an essential sector of a river’s natural filtration process as a sink for pollutants [7]. The construction of dams decreases downstream sediment delivery, with the Three Gorges Dam retaining around 151 Mt/yr, causing significant erosion of the riverbed downstream and coarsening of sediments, all affecting the natural hydrological cycles of the river [7]. The sediment's pollutants are often allowed to re-enter the water, causing secondary pollution [7]. PFAS concentrations vary depending on the source, test location, and season. In extremes, levels as high as 2900 ng/L were found in the

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surrounding river of fluorine chemical plants or fluoropolymer factories [8]. The proximity of the Yangtze River to urban centres also exacerbates both pollution of the river, as well as civil health concerns [8]. Average numbers range from around 60 ng/L to 130 ng/L in areas of varying pollution. Without precise PFAS regulations in China, we can compare these concentrations to standards in the US, with the EPA proposing the lifetime health advisory for PFAS and PFOA at 70 ng/L [9,10]. Perfluorooctanoic acid (PFOA) accounts for about 90% of the total content of PFAS in the Yangtze River water, while short-chain PFASs are concentrated more in the sediment [7]. The proliferation of PFAS in the Yangtze River causes bioaccumulation of PFAS in the body could result in cancers such as testicular cancer and kidney cancer, as well as damage to the liver and kidneys [5,8,2]. PFAS has also shown its effects on the reproductive system and early development, even jeopardizing cardiovascular and neurological health [5,8,2].

2.2. Treatment choices

We chose three treatments to consider and compare in the context of the Yangtze River. We reviewed foam fractionation, activated carbon, and reverse osmosis to address the breadth of our analyzed treatments. These three cover all major bases concerning modern PFAS treatments; activated carbon is one of the most widely used forms of treatment commercially, while reverse osmosis belongs to the subcategory of membrane filtration, also one of the notable methods of PFAS removal. Lastly, we chose foam fractionation for its novelty, with its relevant use only discovered in the 2010s and its promotion as an emerging technology for PFAS treatment beginning around 2017-2018. These three methods focus similarly on long-chain fluorocarbons, allowing for a more equal and relevant comparison, as the PFAS in the Yangtze River water consists of over 90% PFOA, a long-chain fluorocarbon. This is why we didn't consider methods like ion exchange, which is not as predisposed to one type of PFAS.

2.3. Criteria

To compare different treatment methods, we have set criteria to weigh the effectiveness of different options. Our three criteria will be effectiveness, environmental impacts, reliability, and ease of implementation. Effectiveness will simply be evaluating the raw removal abilities of the respective treatments under conditions similar to that of the Yangtze River. Next are our two secondary concerns, environmental impacts and reusability, which support our overarching goal of pollution removal from the Yangtze River. Environmental impacts will specifically be concerned with the waste generated from the treatment, its adverse health and environmental effects, and the adverse effects implementation could have on the environment and people. Reusability will be concerned with the reusability of treatment materials, the long-term consequences of this treatment, and the future-proof and sustainable option. Lastly, one potential criterion we could have considered was the ease of implementation. This would consider the background factors of a solution's implementation, such as monetary costs, ease of material manufacture or acquisition, and potential policy or logistical roadblocks. We chose not to add this consideration in our analysis as, in the long run, the cost of implementation will not be significant. In general, our analysis will also adhere to the conditions of the Yangtze River, specifically the pH levels and the temperature, turbidity, and PFAS concentration levels. The pH of the Yangtze ranges from 7.0 to 8.5, with small deviations in industrial and urban areas [7]. The temperature ranges from 20 - 30 C^o in the summer to 5 - 15 C^o in the winter, and the turbidity is high, especially during rainy seasons [7]. Lastly, we will review

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studies whose PFAS concentration is within 2 orders of magnitude from 100 ng/L, approximating the natural conditions while allowing for some breadth [8].

2.4. Treatments introduction

In this section, I will briefly introduce each treatment method and touch on its history and various aspects considered in our evaluation.

2.4.1. Foam fractionation

Foam fractionation is a relatively newly discovered method of PFAS removal. In general, foam fractional is a separation process by which inorganic and organic ions, molecules, colloidal particles, and suspended solids are floated from aqueous solutions with a rising stream of bubbles [11]. Foam fractionation is often confused with foam floatation: flotation generally describes removing particulate materials by bubbling, and foam fractionation indicates the foaming of dissolved materials by adsorption onto bubble surfaces [11]. The concept of foam fractionation was first discovered in the 1960s by Robert Lemlich of the University of Cincinnati during an attempted characterization of a model of adsorptive bubble separation processes. Foam fractionation was only marginally developed until the mid-2000s when particle separation and PFAS removal became more mainstream. Most foam fractionations are done in a long cylindrical tube with a porous bottom to pass through the air and create bubbles. Relying on the natural tendency of surface active materials to accumulate at bubble surfaces and become trapped in thin film lamellae as foam drains, PFAS is carried to the top and removed as foam. This process is characterized by its low cost and ease of use. One downside of this process is that though it removes PFAS, it doesn't result in the destruction or degradation of PFAS. However, the PFAS concentrated film produced by foam fractionation exponentially facilitates conventional methods of PFAS destruction, such as thermal treatment, alleviating inefficiency and energy consumption issues.

2.4.2. Reverse osmosis

Reverse osmosis is part of the larger family of membrane filtration, as is nanofiltration, ultrafiltration, and microfiltration, in increasing filtration pore size. Membrane filtration, in general, is based on the membrane's ability to separate molecules and particles based on their different sizes and characteristics. The driving force of this separation is the difference in pressure on the two membrane sizes. Reverse osmosis uses water pressure to push the polluted water through the membrane, giving it the advantage of more effective filtration compared to methods like standard osmosis. Scientifically, osmosis was discovered in 1748 by Jean-Antoine Nollet, a French clergyman and physicist, though this process has been happening naturally for millions of years [12]. This topic wouldn't be scrutinized for another 2 centuries until the 1940s, when this process was investigated as a possible desalination treatment [12]. In 1959, the first functional reverse osmosis membrane was created, and the term reverse osmosis was coined due to the process being a reverse of natural osmosis [12]. The drawback of this treatment includes wasting a considerable amount of water, especially polluted water, which may lead to secondary PFAS pollution as it also doesn't degrade or destroy removed PFAS [13]. Reverse osmosis is relatively expensive in installation and maintenance, with scaling and fouling of the membrane commonplace [13]. Due to these factors, the wide-scale use of reverse osmosis is usually avoided.

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2.4.3. Activated carbon

Activated carbon is one of large corporations and governments' most widely used forms of PFAS filtration. As an absorptive treatment, activated carbon involves the adhesion of molecules, ions, or particles to a solid surface, where its highly porous structure and extensive surface area traps and removes a wide variety of contaminants such as PFAS [14]. Activated carbon uses physical forces (van der Waals forces) to attract and hold pollutants on its surface [14]. Of the two main types of activated carbon, granulated activated carbon is generally used in larger treatment systems, while powdered activated carbon is often applied in smaller, point-of-use systems [10]. This treatment dates back to Egyptian medicinal processes in 1500 BC, with modern applications becoming apparent in gas masks during WW1 and 21st-century water treatments. The downside of active carbon treatments is their reusability. PFAS-saturated activated carbon requires energy-intensive treatments to reuse. Furthermore, it is also very dependent on water chemistry, such as pH and the presence of other substances. Lastly, activated carbon cannot destroy or degrade PFAS, potentially becoming a source of secondary pollution.

3. Results

This section will include our researched data and analysis on foam fractionation, reverse osmosis, and activated carbon according to our three criteria. We will initially discuss each criterion separately and combine the analyses of foam fractionation, reverse osmosis, and activated carbon filtration in its entirety during the conclusion.

3.1. Effectiveness

This first criterion will concern the raw effectiveness of the foam fractionation, reverse osmosis, and activated carbon, compared in removal percentages when tested with PFAS-polluted water. Concerning experimental conditions, we included only experiments done between 7.0 and 8.3 pH, with one exception in reverse osmosis. We will also only consider treatments without external aids such as surfactants and catalysts, specifically foam fractionation, which is often employed with surfactants to make the PFAS more hydrophobic, which aids the foaming process [15]. The margin left by the general PFAS concentrations in the Yangtze River, at around 100 ng/L, is substantially more diluted than any concentrations from other papers. Accordingly, we opened our search to concentrations within two magnitudes of 100 ng/L, including concentrations from 1 ng/L to 10 μg/L. Due to constant fluctuations in circumstantial PFAS concentrations, the concentration range is still realistic and significant. Lastly, we will compare the removal efficiency of PFOA, the most prevalent PFAS in the Yangtze River, and take general PFAS removal into account when sufficient data is lacking.

3.1.1. Timeframe

A significant consideration for effectiveness, the treatment lengths of foam fractionation, activated carbon, and reverse osmosis play a role in overall treatment efficiency when employed on a larger scale. Of the three treatments, reverse osmosis has a significantly longer time requirement, with treatment times ranging from 2 hours to over 60 hours, depending on factors like the type of membrane, filtration system, etc [16]. In comparison, foam fractionation and activated carbon take a relatively shorter time. Foam fractionation treatments can take anywhere from five minutes to two hours, with results stabilizing at around twenty minutes [15]. Activated carbons take a similar

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amount of time, from three to thirty minutes [14]. To conclude, activated carbon and foam fractionation take similar amounts of time, while reverse osmosis takes significantly longer, one of the reasons it is used less commercially.

3.1.2. Foam fractionation - effectiveness

Under numerous studies, foam fractionation can give many numbers regarding PFOA and PFAS removal. This is usually due to discrepancies between different experimental conditions, such as pH, initial concentration, and foaming time. In our study, we have mainly evaluated the results in [15] shown in Table 1(We et al. 2024), as their study provides a very comprehensive stockpile of various studies done in various conditions, as well as with the original studies and notes regarding catalysts and surfactants used. We isolated the studies of relevance, the ones relating to conditions similar to that of the Yangtze River in pH and initial concentration, and compiled the data into Figure 1 to showcase the PFOA removal rates and the removal efficiency of general PFAS concerning the different studies. From these graphs, we can see trends in the removal efficiency of foam fractionation. The PFOA removal percentage stays stable at around 96 - 97% across the different studies. In contrast, the PFAS percentage varies by a notable margin across different tests, ranging from 95% to 51% removal efficiency [15]. This is likely due to the various PFAS-type concentrations in the general PFAS tested. As foam fractionation is focused primarily on short-chain fluorocarbons, the varying presence of long-chain fluorocarbons in the tested water may cause fluctuating results. We averaged the values to obtain our final PFOA and PFAS removal percentages. By taking the average of each study before averaging all the studies as a whole, we eliminated the possibility of having one study overpower all other data due to the production of numerous data, as well as mitigate the effects of environmental factors that may have impacted numbers in specific studies. In the end, the number we obtained for PFOA removal is 96.78%, while the general PFAS removal percentage is 73.57%.

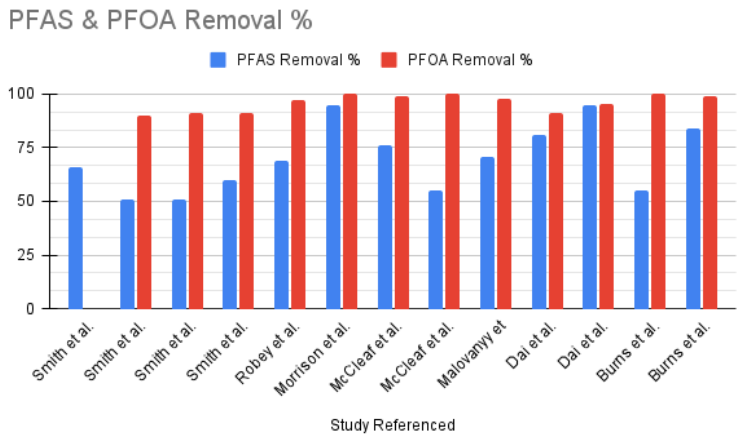

Figure 1. Graph of relevant data on PFOA and PFAS removal percentages against the original studies

3.1.3. Reverse osmosis - effectiveness

Reverse osmosis and membrane filtration are considered one of the more niche PFAS removal solutions, usually only performed at a smaller scale due to energy requirements, waste produced,

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and tedious maintenance. As reverse osmosis and membrane filtration rely on physically separating particles of different sizes and characteristics, the pore sizes and membrane material control the filtration. For our examination, we will be considering conventional reverse osmosis models, all of which will be shown in Table 1. The traditional reverse osmosis methods utilize polyamide selective layers with a pore size of 0.1 nanometers [17]. Our results in this section are mainly based on [17], which has compiled numerous studies on removal rates of nanofiltration and reverse osmosis shown in Table 2. This said, there was very little data in realistic conditions. Much of the previous studies were done in extremely acidic conditions of 5 pH, two pH lower than our margin's base of 7.0 pH. The only significant data on realistic conditions was a study done by [18], which reported a value of >99% PFAS removal in an environment of 7.0 ± 0.4 pH [17]. We cross-referenced this removal percentage with other review papers and their sources and obtained an average of around 96% [17,19]. Due to the wide range of sources and often varying conditions, we could not justify being more precise. Furthermore, we also decided to investigate the numerous tests done under acidic conditions presented in [17]. We found that they also have similar but slightly higher removal rates, signifying that acidification of the treated water would have similar, if not a little higher, removal rates for general PFAS.

Table 1. Membrane models, selective layers, and pore sizes in reviewed studies [17]

Membranes	Model	Material of selective layer	MWCOa(Da)	Pore size(nm)	Contact angle(°)	Isoelectricpoint	Zeta potential (mV)	Waterpermeability(L·m-2-·h-1·bar-1)
Commercial RO	SG	Polyamide	100	0.1	72.9	NA	-12.3(pH=4)	2.3
	LFC	Polyamide	100	0.1	76.5	p=3.1	4.0(pH=4)	4.0
	LFC3	Polyamide	<100	0.1	35.0	NA	3.0-3.8 (pH=4)	2.8
	BW30	Polyamide	98	0.1	43.7	NA	3.0-3.6(pH=4) -10.0(pH=7)	4.0
	ESPA3	Polyamide	NA	0.1	NA	NA	14.7(pH=4) 15.0(pH=4)	7.5
	ESPA-2540	Polyamide	100	0.1	NA	pH<4	NA	5.9
	XLE	Polyamide	98	0.1	67.2	NA	-30.0(pH=7)	4.8
	SW30XLE	Polyamide	<100	0.1	61.4	NA	-15.0(pH=7)	2.0

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Table 2. Relevant examined reverse osmosis tests with initial concentrations and feed water acidity [17]

Membrane	Type	Feed water			PFAS Rejection(%)
		pH	Concentration(μg·L^{-1}) Compositions		
Commercial	LFC3	4.0	1.0×10^4(PFOS)	DI water	>99.0(PFOS)
RO		4.0	5.0×10^2-1.6×106(PFOS)	DI water	>99.0(PFOS)
	BW30	4.0	5.0×10^2-1.6×10^6(PFOS)	DI water	>99.1(PFOS)
		3.5-7.1	1.0×10^5(PFHxA)	DI water	96.0->99.9(PFHxA)
		4.0	5.0×10^2-1.6×106(PFOS)	DI water	>99.0(PFOS)
	ESPA3	4.04.0	1.0×10^4(PFOS)5.0×10^2-1.6×10^6(PFOS)	DI waterDI water	>99.0(PFOS)>99.0(PFOS)
	ESPA-2540	7.0±0.4	0.3-58.4(PFPeA,PFHxA,PFHpA,PFOA,PFPrS,PFBS, PFPeS,PFHxS,PFHpS,PFOS)	AFFF Spiked water	>99.0(ALL)
			0.1-2.7(PFPeA,PFHxA,PFHpA,PFOA,PFPrS,PFBS, PFPeS,PFHxS,PFHpS,PFOS)	AFFF ground water	
	XLE	3.5-7.1	1.0×10^5(PFHxA)	DI water	>97.5(PFHxA)
	SW30XLE	3.5-7.1	1.0×10^5(PFHxA	DI water	>96.0(PFHxA)

3.1.4. Activated carbon - effectiveness

Activated carbon is one of the most commercially used forms of PFAS treatment alongside ion exchange, mainly due to ease of use, time frame, etc. Consequently, numerous studies have been done on many types of activated carbon. Unfortunately, most data collected are from experiments done in much higher initial PFAS concentrations than realistic for a natural environment like the Yangtze River, and up to over five orders of magnitude larger than in our accepted margin. From [20], we obtained environmentally relevant data regarding adsorption percentages of PFOA adsorption and both hydrophobic and hydrophilic PFAS adsorption, as shown in Figure 2. We also obtained one relevant experiment's data from [10]. However, since the removal percentages recorded were especially small, less than 0.1%, likely because low initial concentrations provided difficulty for concentration measurements, we ruled this out as an outlier. We have formatted the data from ([10]) and Figure 2 for different types of activated carbon in Figure 3 to help better illustrate its performance. The data shows a notable difference in adsorption percentages in different types of activated carbon and PFAS, with vc-activated carbon having a 2.5 % hydrophobic PFAS removal rate. In comparison, rb-activated carbon has 97.5 % PFOA removal. Ultimately, for our final comparison data, we decided to average out the data in Figure 3 as our study attempts to evaluate the method as a whole, which calls for representation from all activated carbon types. Our

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final PFOA removal rate for activated carbon was 77.12%, while the general PFAS removal rate, generated from averaging the hydrophobic and hydrophilic PFAS removal rates, was 41.38%.

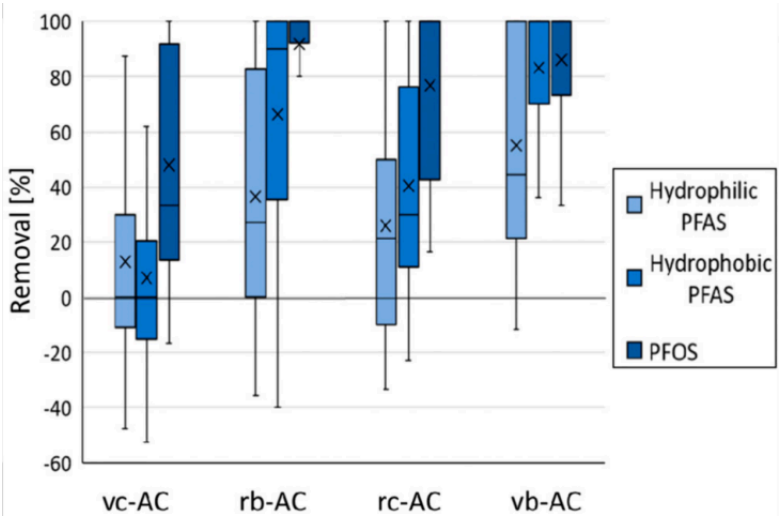

Figure 2. (Cantoni B. et al. 2021): graph of the adsorption percentages for hydrophobic and hydrophilic PFAS and PFOA of four types of activated carbon

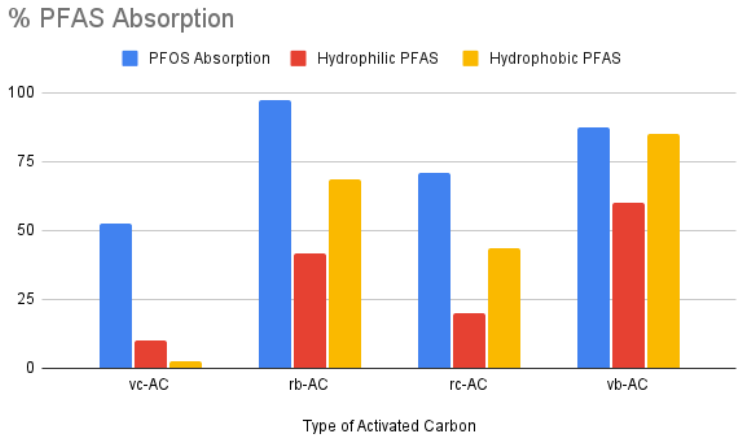

Figure 3. Graph of average adsorption percentages shown in Figure 2

3.1.5. Effectiveness criteria conclusions

After analyzing the effectiveness of PFAS and PFOA removal by foam fractionation, reverse osmosis, and activated carbon, there are many things to note. Regarding raw effectiveness, the numbers show a notable increase in PFAS and PFOA removal from foam fractionation and reverse osmosis compared to activated carbon, as shown in Figure 4. Activated carbon showed a visible decrease in PFOA removal, at around 18-20% compared to the other two treatments, while the general PFAS removal was lower by around 30%. We deemed this most likely due to various experimental and analysis factors, as in the case of activated carbon, we averaged various types of activated carbon, many of which had varying results. Though activated carbon types may be able to match and even outperform foam fractionation and reverse osmosis, the consideration of suboptimal types significantly lowered the average adsorption percentage. Another factor could have been

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attributed to activated carbon's low effectiveness when dealing with short-chain fluorocarbons, as even though all of our analyzed treatments are focused on long-chain fluorocarbons, the variations in short-chain fluorocarbon concentration in the general PFAS samples could have affected the activated carbon most significantly. It is still significant to acknowledge the time frame assessment of the three treatments, with foam fractionation and activated carbon being notably superior to reverse osmosis in terms of time efficiency. In conclusion, foam fractionation is the superior treatment solution from an effectiveness standpoint.

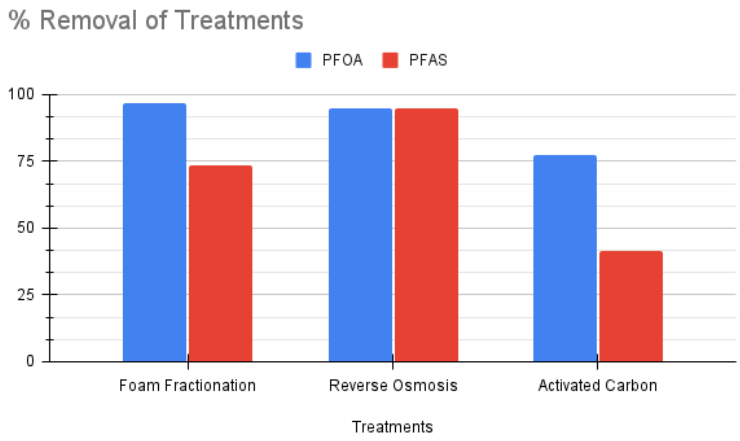

Figure 4. General removal percentages of PFOA and PFAS by foam fractionation, reverse osmosis, and activated carbon as concluded in our analyses

3.2. Environmental impact

We will now consider the environmental impacts of foam fractionation, reverse osmosis and activated carbon throughout the entire process of the treatment. Realistically, the environmental impact should be equivalent when evaluating different PFAS treatment methods because primary and secondary pollution from implemented treatments would be entirely counterintuitive to water treatment. As a result, to solidify an environmentally friendly option, an evaluation of the environmental impacts brought by each treatment method is necessary. In this criterion, we will quantify the extent of the environmental impact of different methods, point out the possible environmental consequences, and offer some possible solutions to certain methods.

3.2.1. Foam fractionation - environmental impact

Foam fractionation creates a highly PFAS-concentrated foam as a waste product of the treatment [16]. If the concentration of PFAS is not subsequently destroyed, pollution of the environment through diffusion is likely, warranting even further treatment. However, the concentrated PFAS can be removed with hydrothermal alkaline treatment, achieving a 99% PFAS mass removal. Alternatively, the small volume of removed PFAS can be blended back into the much larger influent flow of the foam fractionation system without significantly affecting the overall PFAS concentrations being treated. Diluting the treated concentrate into the much larger input flows could also eliminate concerns about the discharging of caustic brine [21]. In some cases, foam fractionation can also lead to the release of PFAS into the atmosphere through the air, increasing the risk of air pollution. Though the impact of such air emissions is minute, it is still a relevant

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consideration, necessitating the employment of a waste gas regulation system to prevent the release of toxic gas [18].

3.2.2. Reverse osmosis - environmental impact

In reverse osmosis, water molecules pass through the membrane. In contrast, the membrane blocks most solutes and impurities like PFAS and remains on the high-concentration side, forming a concentrated solution [1], as shown in Figure 5. The concentrate typically requires further treatment or disposal through incineration and chemical degradation, releasing greenhouse gases. The greenhouse gases and other byproducts formed during the process will contaminate the air and water resources if not properly treated [22]. Moreover, the disposal of concentrated PFAS remnants is an energy-intensive treatment method because of the high pressure that is always required to drive the whole process, often leading to extensive use of non-renewable energy. Non-renewable energy, such as fossil fuels, will pollute the air by releasing carbon dioxide and other greenhouse gases and destroying the ozone, contributing to global warming. Furthermore, the membranes themselves could also serve as a type of pollutant, with frequent membrane clogging and membrane fouling due to the deposition of unwanted particles on the pores of the membranes, resulting in both more waste and potentially secondary pollution [23].

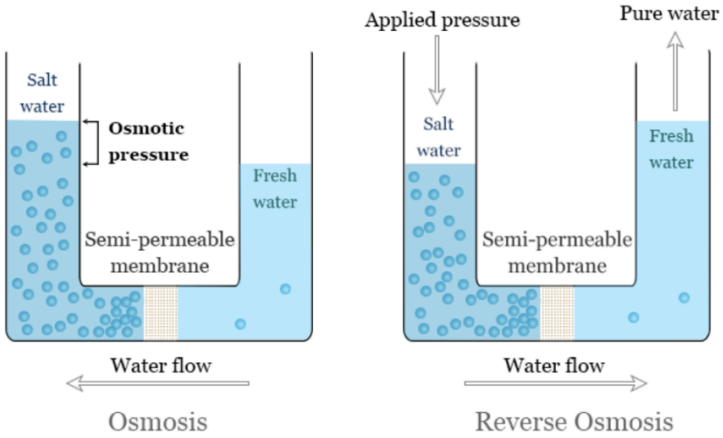

Figure 5. Diagram of reverse osmosis processes in comparison to the processes of conventional osmosis

3.2.3. Activated carbon - environmental impact

When using activated carbon to absorb PFAS, most water treatment industries will reuse a granular activated carbon array for about five cycles, with activated carbon deactivation leading to an adsorption efficiency decrease of about 30% because of the saturated pores on carbon surfaces. As a result, organic solvents such as methylene chloride are required to enhance granulated activated carbon's absorption efficiency. However, using these solvents produces extensive amounts of spent regenerant, which diffuses into the drinking water, contaminating the water resources and becoming a health hazard. Therefore, these solvents require certain separation methods to extract and dispose of water resources [24]. Moreover, as the recovered PFAS solvents by activated carbon are fully immune to chemical degradation methods, they require incineration [3]. During incineration, fluorinated greenhouse gases will form, harming the atmosphere and contributing to global warming. Controlled measures during the thermal treatment process are required to alleviate the health problems brought by toxic gas emissions. For instance, employing an electrostatic

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precipitator to capture and neutralize harmful PFAS gases or a proper ventilation system during treatment would greatly alleviate the issue [19].

3.2.4. Environmental impact criteria conclusions

This section provided many insights into the environmental consequences of each treatment. Activated carbon requires organic solvents that are toxic and harmful to the environment to reactivate after several cycles of usage, which releases significant amounts of greenhouse gases into the atmosphere and leaves short-chain PFAS in the water, which needs further disposal. Reverse osmosis forms a concentrated stream of unfiltered PFAS whose destruction by incineration requires large amounts of energy, making the method unsustainable. Reverse osmosis also requires cleaning or disposing of the membrane after clogging and fouling. Though producing a certain amount of concentrated PFAS, foam fractionation causes relatively little negative effects on the environment. The concentrated PFAS can relatively easily be removed by the hydrothermal alkaline treatment efficiently without forming any secondary pollution and byproducts. Therefore, by evaluating the proponents and detriments of each treatment method, foam fractionation is the most environmentally friendly treatment due to its simple byproduct removal methods, relatively low greenhouse gas emissions, and sustainable energy consumption.

3.3. Reusability

The third criterion will concern the reusability of foam fractionation, reverse osmosis, and activated carbon. Generally, cities often build large water treatment stations, requiring thousands of tons of material used to treat polluted water. Should these materials not be properly reused, significant resources, time, and capital will be wasted. Therefore, in the context of the Yangtze River, reusability is essential given the river's significant size.

3.3.1. Foam fractionation

In surface activation foam fractionation, the increase of pressure and gas density can minimize the bubble size and increase the solubility of O_3 up to 1.7 times that of conventional foam fractionation5. This could save significant amounts of energy and increase the treatment's durability. Although this result cannot be directly linked with reusability, the end goal of recycling is the same. Another result is that the micro ozone bubbles can produce less innoxious by-products in leachate and wastewater than conventional ozonation. According to the stronger hydrophobicity of the ozonated bubbles, a lesser extent of boundary water on the surface of bubbles can be carried out to the reservoir tank. The amount of boundary water surrounding the bubble strongly affects the wettability of the foam recovered, leading to the ozone system being 2 to 4 times drier than the air system. The lowering of the wetness of formate in the atmosphere makes surface activation foam fractionation an environmentally sustainable process for removing PFAS contaminants from water, such as the Yangtze River. This also saves significant costs for the final disposal of waste products and reduces site storage requirements [7]. Another advantage of surface activation foam fractionation is that no absorbent is required, and no chemical reagents are acquired.

3.3.2. Reverse osmosis

Though not known for its reliability, studies suggest reverse osmosis can exhibit some regeneration qualities. The result shows that when the salt removal rate is 39% to 66%, the interception rate of

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damaged reverse osmosis membrane on PFOA and PFOS is greater than 85% [11]. This means that the recycling of waste reverse osmosis membrane greatly affects the development of a circular economy and the realization of carbon neutrality. To minimize performance degradation due to fouling, the membranes must be cleaned and maintained often, leading to costly maintenance. Due to its many flaws, such as high energy and cost requirements and a lack of significant regeneration abilities, we conclude that reverse osmosis has very low reusability.

3.3.3. Activated carbon

According to an experiment in mini-column studies, scientists utilized both sterilized and unsterilized granulated activated carbon to differentiate between the adsorption and the possible degradability of PFOA and PFOS over the activated carbon. Many factors could affect the removal of PFOA and PFOS, such as temperature, influent concentration, and empty bed contact time (EBCT) [25]. Surprisingly, old activated carbon samples were still found to eradicate 40–55% of PFOS and 20–40% of PFOA. These outcomes suggest that the old activated carbon in drinking water treatment plants could remove PFAS without any modification or further action. However, an important thing to consider is that the contaminants may have a very slow pore diffusion rate due to a higher tortuosity in the old activated carbon [7]. Due to its reusability, this method is very cost-saving, with data showing that city-wide use of activated carbon to treat PFAS can save an installation cost of 46 million gallons and an operational cost of 2.9 million gallons for the treatment of 44 million gallons per day. Compared to other water treatment methods, it is the most affordable method because this saves 2 to 3 million gallons per day, even when the average cost of power is factored in.

3.3.4. Reusability criteria conclusions

Our conclusions are such by comparing all those three methods—foam fractionation, reverse osmosis, and activated carbon. Foam fractionation, which can treat long-chain in PFAS, is very efficient under the ozone system. Due to having no by-products and being cost-effective, foam fractionation could be considered a sustainable process for treating PFAS. Activated carbon can be reused even if it is already used and old. With the advantage of cost-saving, granulated activated carbon is a choice of water treatment for broad areas in many cities. Although the only method that can be reused even when damaged, reverse osmosis has far more disadvantages, such as high-cost energy requirements, rendering it unfit for commercial use. Therefore, by evaluating the differences between the three approaches, activated carbon proves the most reusable.

4. Conclusions

In our evaluation and comparison of foam fractionation, reverse osmosis, and activated carbon as treatment methods for PFAS in the Yangtze River, we have found that each method exhibits unique strengths and limitations across the criteria of effectiveness, environmental impact, and reusability. From an effectiveness perspective, foam fractionation and reverse osmosis demonstrated superior performance in PFAS and PFOA removal compared to activated carbon, likely due to the type used and its limitations in addressing short-chain fluorocarbons. Regarding environmental impact, foam fractionation emerged as the most environmentally friendly treatment method because it efficiently destroys byproducts and minimizes greenhouse gas emissions, coupled with its relatively low energy consumption. Activated carbon requires toxic solvents for reactivation and generates concentrated

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PFAS streams that necessitate further disposal. Reverse osmosis consumes significant energy and generates concentrated PFAS waste streams requiring incineration. Finally, considering reusability, activated carbon demonstrated the greatest potential, allowing for reuse even under suboptimal conditions. Foam fractionation, on the other hand, offers energy savings through recycling and lacks the disadvantages of reverse osmosis, such as membrane fouling, high maintenance, and high monetary and energy costs. In conclusion, while all three treatment methods have their merits, foam fractionation emerges as the most favourable overall due to its superior performance in PFAS and PFOA removal, minimal environmental impact, and reasonable reusability potential, making it a promising solution for addressing PFAS pollution in the Yangtze River. In the future, further studies could build on the topic explored in this paper by delving deeper into the solvents and catalysts, evaluating best-case scenario treatments, and potentially researching policies, monetary costs, and ease of material manufacturer, criteria we chose to ignore.

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