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Per-and polyfluoroalkyl substances (PFAS) removal from water by aeration.

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La imaginación es más importante que el conocimiento. El conocimiento es limitado. La imaginación rodea el mundo. Albert Einstein

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SUMMARY

Conventional water treatment plants do not completely eliminate emerging contaminants that, although they occur at low concentrations, can be harmful. Among them, per- and polyfluoroalkyl substances (PFAS), present in many everyday products, can provoke adverse health effects. Due to the growing concern, it is necessary to develop new technologies for their elimination. The main objective of this work is to evaluate the effectiveness of the removal of these contaminants by aeration. To date, this technology, which commonly consists of exposing water to an air flow in order to volatilize contaminants, has been scarcely investigated for the treatment of PFAS. To this end, a literature review related to the aeration process for the removal of PFAS from water was conducted, resulting in the identification of seven research articles. First, two removal mechanisms were proposed, volatilization-stripping and aerosol formation. In addition, the effects of the main factors in the aeration process on the removal of PFAS from water were analysed. The main results indicated that, at low concentrations, PFAS can be effectively removed. However, when a certain concentration threshold is exceeded, foams are formed which decrease the efficiency of the process. In addition, it was observed that the removal efficiency improves with increasing compound chain length, ionic strength and air flow rates. Regarding the pH of the aqueous medium, no conclusive conclusion was obtained due to the ambiguous results obtained in the different studies reviewed. Although other parameters were less investigated, such as the effect of temperature and the coexistence of other substances, were also investigated since they could influence the efficiency of the process. In conclusion, the aeration process is presented as a promising alternative for the removal of PFAS from the aqueous medium.

Keywords: Aeration; Microcontaminants; PFAS; Water treatment.

RESUMEN

Las plantas de tratamiento de aguas actuales no eliminan completamente contaminantes emergentes que, aunque aparecen en bajas concentraciones, pueden resultar perjudiciales. Entre ellos, las sustancias per- y polifluoroalquiladas (PFAS), presentes en muchos productos cotidianos, pueden presentar efectos adversos en la salud. Debido a la creciente preocupación, es necesario desarrollar nuevas tecnologías para su eliminación. El objetivo principal de este Trabajo es evaluar la efectividad de la eliminación de estos contaminantes mediante aireación. Hasta la fecha, esta tecnología, que consiste en la exposición del agua a un flujo de aire con el fin de volatilizar contaminantes, ha sido escasamente investigada para el tratamiento de los PFAS. Para ello, se llevó a cabo una revisión bibliográfica relacionada con el proceso de aireación para la eliminación de PFAS del agua, resultando en la identificación de siete artículos de investigación. En primer lugar, se propusieron dos mecanismos de eliminación, por volatilización-stripping y por formación de aerosoles. Además, se analizaron los efectos de los principales factores en el proceso de aireación para la eliminación de PFAS del agua. Los principales resultados indicaron que, a bajas concentraciones, los PFAS pueden ser eliminados de manera muy efectiva. Sin embargo, cuando se supera un cierto umbral de concentración, se forman espumas que disminuyen la eficiencia del proceso. Además, se observó que la eficiencia de eliminación mejora al aumentar la longitud de la cadena del compuesto, la fuerza iónica y los caudales de aire. En cuanto al pH, no se obtuvo una conclusión concluyente debido a los resultados ambiguos obtenidos en los distintos estudios. También se evaluaron otros parámetros de los que se recogen menos datos, como el efecto de la temperatura y la coexistencia de otras sustancias, los cuales podrían influir en la eficacia del proceso. En conclusión, el proceso de aireación se presenta como una alternativa prometedora para la eliminación de los PFAS del medio acuoso.

SUSTAINABLE DEVELOPMENT GOALS

In 2015, the United Nations presented with the intention of achieving a better future by 2030, the Sustainable Development Goals (SDGs), a set of 17 goals designed to address major global challenges such as poverty, health, education and the environment.

The present project contributes to several SDGs, mainly SDG 6 "Clean Water and Sanitation" as it focuses on the elimination of water pollutants, specifically PFAS from water, which is crucial to ensure access to safe drinking water. This involves reducing exposure to chemicals that cause serious diseases, thus improving people's health and well-being, which SDG 3 "Health and Well-being" is based on. In addition, research into the elimination of PFAS promotes better management of these chemicals and encourages more sustainable practices, also contributing to SDG 12 "Responsible Production and Consumption". Likewise, improving water and soil quality contributes to a healthier and more resilient environment in the face of climate change, supporting SDG 13 "Climate Action". And finally, removing PFAS from water protects aquatic ecosystems and marine biodiversity, preventing pollution of oceans and rivers, which is key to SDG 14 "Underwater Life".



1. INTRODUCTION

Water is an essential resource for life on Earth, but although 70% of the Earth's surface is covered by water, but just a small fraction is suitable for human consumption. Water quality and its availability is a current global issue, which has been increasing due to urban, agricultural and industrial activities [1].

The figures are really worrying as today, there are about 884 million people in the world who do not have access to safe drinking water and 2.6 billion people who lack access to basic sanitation, which account for 40% of the world's population. Together with urban, agricultural and industrial activities and other factors such as climate change, human activity and population growth, it is estimated that by 2030, water use is projected to increase by 40% [2].

Comparing analyses at the beginning of the 20th century, water consumption is currently 6.5 times higher and is expected to continue to increase significantly [3].

Nowadays, the concern for water resources is constantly increasing, both for its availability and its quality. Prolonged periods of drought, which are becoming more frequent due to climate change, threaten water availability. In addition, water quality is compromised by pollution from different sources.

1.1. CONTAMINANTS OF EMERGING CONCERN

Environmental pollution is one of the biggest problems we face today and together with climate change. It threatens species and ecosystems, putting life on the planet at risk and water pollution aggravates this situation even more.

Among the various actions that can be taken to improve the situation of water pollution, improving wastewater treatment stands out due to its significant contribution to water pollution when discharged into rivers and seas without proper treatment. An efficient use of water, the reduction of the use of chemicals and the implementation of adequate infrastructures for water purification are essential to reduce this problem [4].

Wastewater treatment plants (WWTPs) are used to treat wastewater and their main objective is to eliminate or minimize water pollution caused by chemicals and organic substances [5].

However, even if these treatments are applied, the complete elimination of certain pollutants cannot be guaranteed. In addition to accidental or point discharges of pollutants that are distributed in the environment in high concentrations, diffuse or point pollution is of even greater concern. This is caused by thousands of compounds whose effects are not so well known and which are present in the environment in very low concentrations.

These emerging pollutants are compounds that have recently been detected in water and there is great concern about their effects on health and the environment. They include several families of compounds, such as drugs and personal care products, pesticides, drugs of abuse, steroids and hormones, polyhydroxyalkanoates (PAHs), microplastics, perfluoroalkylated and polyfluoroalkylated substances (PFAS), among others [6].

Because of this, water that is mainly intended for human consumption requires a lot of attention and that is why drinking water regulations are becoming more and more restrictive. Specifically, Spain is up to date with the regulations on drinking water, last January 10th was published the Royal Decree 3/2023, which establishes the technical-sanitary criteria for the quality of drinking water, its control and supply [7].

The new regulation introduces a risk-based approach with three key components: the water administration will be responsible for assessing and managing risks in drinking water catchment areas; the operators of supply infrastructures will be responsible for risk management from catchment to delivery to the user; and the owners of priority buildings will have to manage risks in indoor facilities [8].

In addition, every 2 years the European Union publishes a Watch List, which is composed of a set of substances selected that they may pose a significant risk to or via the aquatic environment and the monitoring data available are insufficient. The purpose is to know their frequency in waters and to evaluate their toxicity, and then those substances may become priority substances [9].

1.2. PER-AND POLYFLUOROALKYL (PFAS)

Among these contaminants of emerging concern, perfluoroalkylated and polyfluoroalkylated substances (PFAS) that consist of a hydrophobic alkyl chain of variable length (fully or partially fluorinated), with a hydrophilic end group, stand out. They are widely distributed in the environment due to their extensive use for decades in numerous commercial and industrial applications because of their unique properties [10,11]. Because of this amphiphilic character their properties include water and oil resistance, chemical and thermal stability, reduced friction, and decreased surface tension [12].

Among its infinite uses are firefighting foams (AFFF), metal coatings, textiles, food packaging and consumer products [10,11].

According to the U.S. Environmental Protection Agency (EPA), it is estimated that there are more than 4,700 different types of PFAS. The best-known substances are PFOS (perfluoroctane sulfonate) and PFOA (perfluoroctanoic acid) [13], whose molecular structures can be seen in Figure 1. The two share that they come from an eight-atom carbon chain (octa-) and fully fluorinated (perfluoro-). The difference lies in the functional group at the end, for PFOA, the carboxylic acid group (-oic) and for PFOS, the sulfonate group (-sulfonate).



These compounds can be harmful to human and animal health and remain in the environment and in our bodies for a long time, which can lead to an increase in their concentration. For this reason, they are commonly known as " forever chemicals" [12].

For this reason, European and national authorities, through EFSA (European Food Safety Authority) and AESAN (Spanish Agency for Food Safety and Nutrition), have conducted diverse studies and have established that the tolerable daily intake (TDI) per body weight is 150 ng/kg for PFOS and 1500 ng/kg for PFOA, without causing adverse health effects.

In addition, it has been legislated in the Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum limits for certain contaminants in food and repealing Regulation (EC) 1881/2006. And also, through Regulation 850/2004 on persistent organic pollutants, Recommendation 2010/1616 /EU on the monitoring of PFAS in food or the recent Royal Decree (RD) 3/2023 establishing the technical-sanitary criteria for the quality of drinking water, its control and supply to have controlled the levels of PFAS to which we are exposed [13]. In fact, the latter legislation establishes that the sum of 20 regulated PFAS cannot exceed 0.10 µg/L. Table 1 shows the most frequent substances in groundwater, surface water and drinking water.

Chemical compound		Molecular formula
PFOA	Perfluorooctanoic acid	$C_8HF_{15}O_2$
PFOS	Perfluorooctane sulfate C ₈ HF ₁₇ O ₃ S	
PFNA	Perfluorononanoic acid	$C_9HF_{17}O_2$
PFHxA PFBA PFHxS PFHpA	Perfluorohexanoic acid Perfluorobutanoic acid Perfluorohexanesulfonic acid Perfluoroheptanoic acid	C6HF11O2 C4HF7O2 C6HF13O3S C6F13COOH

Table 1. Most frequent PFAS in waters

Moreover, the interest of the scientific community in perfluoroalkylated and polyfluoroalkylated compounds is of particular concern. Publications in Web of Science related to "PFAS" as of June 3, 2024, total 6128 papers. Although the database has articles since 1959, Figure 2 shows their evolution over the last 10 years with the intention of presenting a current graph. As can be seen, research on this topic is progressively increasing.



Figure 2. Evolution of "PFAS" publications

1.3. REMOVAL TECHNOLOGIES

To improve the water pollution situation, the application of removal technologies is very crucial. These techniques are designed to eliminate or reduce the presence of contaminants in water, thus ensuring its safety and potability. Ranging from conventional methods to more advanced techniques, these technologies cover a wide range of tools and processes to suit different types and levels of contamination.

1.3.1. Conventional water treatments

Conventional technologies present in Wastewater Treatment Plants (WWTP) and Drinking Water Treatment Plants (DWTP) are fundamental in water treatment. However, in the presence of persistent and emerging pollutants, advanced technologies have emerged that seek a more efficient and complete elimination.

The objective of Wastewater Treatment Plants (WWTPs) is to protect the environment by treating process waste flows through a combination of primary, secondary and tertiary treatments [14].

- Primary treatment consists of reducing total suspended solids (TSS) with a gravitational sedimentation process and eliminating floating objects [15].
- Secondary treatment is based on a biological process in which microorganisms are responsible for treating wastewater by removing suspended and dissolved organic compounds [15]. One of the most common processes is the activated sludge system where microorganisms that are present in the wastewater are used to convert dissolved organic matter into simpler compounds [16].
- Finally, tertiary treatment includes additional physicochemical processes to improve pollutant removal. The most used treatments in this stage are activated carbon adsorption processes, chemical coagulation, and sand or membrane filtration [15].

Currently in Spain there are more than 2000 WWTPs, which in total treat about 4000 hm³, which would mean about 245 litres of treated water per inhabitant per day [17]. The percentage of WWTPs with tertiary treatment is below 30%.

Although the objective is to reduce pollutants, WWTPs are the main transporters and point sources of PFAS to the environment [18-20].

This occurs because waters that are contaminated with PFAS enter the station from domestic and industrial sources and leachates from landfills [19]. But these substances are not removed in an effective way, but, on the contrary, they are transported with the effluents or split in the sludge during biological treatment. In addition, incoming PFAS precursors, which may be chemicals used in various industrial and commercial applications, can be transformed into chemicals that cannot be further degraded and eventually lead to higher PFAS concentrations in the effluent [21].

In this regard, Ilieva et al. analysed data from 161 WWTPs worldwide and evaluated the 13 most frequent PFAS reported in these plants. They observed that biological treatments such as membrane bioreactors, combination of two or more biological treatments and together with biofilm processes demonstrated the best PFAS removal rates. Furthermore, they found that

adding tertiary treatment such as ultrafiltration (UF) membranes and sand filters did not result in improved removal [15].

A schematic of the stages of a WWTP can be seen in Figure 3.



Figure 3. Scheme of the stages of a WWTP.

On the other hand, the Drinking Water Treatment plant (DWTP) is responsible for carrying out the necessary processes to ensure that the water has the minimum quality and is safe for human consumption.

There are few studies on the presence of PFAS in drinking water compared to the numerous studies that exist on their presence in surface and groundwater [22].

Although there are cases of the presence of PFAS in the magnitude of mg/L concentrations, they are typically in the sub ng/L range, provided there is no obvious point source of contamination near the water intake for the system [23-25].

Studies on the presence of PFAS in drinking water usually focus on PFOS and PFOA compounds, which are the most detected. However, other compounds such as PFBA, PFPA, PFHxA, PFHpA, PFNA, PFUnDA, PFHxS, and FOSA have also been found in drinking water [26-28].

Studies of PFAS plants quickly demonstrated that conventional treatment processes could not effectively remove PFAS.

Rahman et al reviewed data from large-scale drinking water treatment plants and showed that, if PFAS are present in raw water, most drinking water treatment processes do not

significantly remove them. These processes include coagulation, flocculation, sedimentation, filtration, biofiltration and oxidation [22].

As for Spain, more specifically in the province of Tarragona Ericson et al. in 2007 investigated the main sources of human exposure to PFAS. In tap water, concentrations for PFOS and PFOA ranged between 0.39 and 0.87 ng/l and between 0.32 and 6.28 ng/L, respectively. PFHpA, PFHxS and PFNA were also detected. In comparison, the analysis of PFAS concentrations in bottled water was much lower. The daily intake per person in the evaluated area was estimated to be around 0.78 to 1.74 and 12.6 ng, respectively assuming a consumption of 2 litres per person per day [29,30].

In 2008 they collected samples again and concluded that, with the data collected, PFOS and PFOA concentrations should not be a risk to human health [31].

Later, in 2012, Domingo et al. conducted a study analysing samples of PFAS concentrations at 3 different stages in the drinking water treatment process in different DWTPs in Catalonia. They first analysed at the raw water extraction site, then after the transformation process to drinking water and finally in the consumption areas. The mean concentration levels obtained for PFOS and PFOA were 1.91 and 2.40 ng/L, respectively. They concluded that the treatment processes caused slight reductions in PFAS concentrations but did not achieve significant changes in the amounts of these compounds present in the untreated water [32].

As can be seen in the conventional processes used in both WWTPs and DWTPs, they do not achieve good removal efficiency of these substances and more advanced processes are required.

1.3.2. Advanced water treatments

Currently, there are several technologies available for the remediation of contaminants of emerging concern that have been tested for the removal of PFAS from water. These technologies fall into two main categories: non-destructive and destructive processes [33].

Some of these technologies that have been investigated are listed below.

- 1. Non-destructive processes:
 - Adsorption techniques: use of activated carbon, biomaterials, minerals, ion exchange resins or polymers and nanomaterials.
 - Membrane technologies: nanofiltration and reverse osmosis.
 - Foam fractionation
- 2. Destructive processes:
 - Advanced reduction.
 - Ultrasonics.
 - Advanced oxidation: chemical, electrochemical and photochemical.
 - Biological remediation.
 - Plasma technology

1.3.2.1. Non-destructive processes

Non-destructive processes for the removal of PFAS from water are based on the physical and chemical separation of these compounds without altering their molecular structure.

Adsorption is a very effective technique for removing many contaminants, including PFAS. It is considered one of the most plausible techniques for water treatment due to its affordable cost, environmental friendliness, high efficiency, simple design, easy operation, and resistance to toxic substances [34].

Wanninayake, on the other hand, reported some limitations of using this process, since the PFAS from the liquid phase must be concentrated in the solid phase and then the saturated material must be adequately treated, and the absorbed PFAS must be transported, stored and destroyed in an optimal way. This whole procedure has high operating and maintenance costs and, above all, high energy consumption [35].

The use of natural adsorbents is an alternative that has the advantage of low commercial cost, high environmental sustainability and high abundance; but shares that it requires a lot of energy for disposal and incineration after use.

One of the most widely used adsorbents is activated carbon, but its disadvantages include regeneration after depletion, decreased efficiency after each regeneration cycle due to carbon loss, and high cost.

The alternative of using ion exchange resins (IXR) presents also some limitations due to these resins are mostly regenerated with organic solvents that require another treatment because of the properties of these solvents. This implies that the procedure has high operating and maintenance costs. Although nanomaterials are very efficient, they present a very high cost compared to other adsorbents. It is therefore necessary to get further insights into the development of efficient, low-cost and environmentally friendly adsorbents.

On the other hand, reverse osmosis (RO) and nanofiltration (NF) processes use semipermeable membranes to separate and remove contaminants from water. They have proven to be very efficient in removing a wide variety of PFAS, but one of the biggest problems is maintaining the membrane in good condition. Thus, performing these techniques on a large scale requires high cost [36].

The foam fractionation technique is a biotechnological process that present numerous advantages, such as being able to separate or concentrate viruses or bacteria and other organic compounds. However, it is a very complex technique on a large scale and, in addition, creating foam generates waste that needs to be further treated [38,39].

Currently, combinations of the aeration technique with other methods, such as ozonation, have been developed, resulting in a process called ozofractionation. This technique has proven to be effective for PFAS removal. However, to ensure optimal results, it is necessary to complement it with other procedures, such as adsorption, filtration and destruction of contaminants. [37].

1.3.2.2. Destructive processes

Advanced destructive treatments for the elimination of PFAS in water are based on the chemical degradation and decomposition of these substances. These methods seek to break the strong carbon-fluorine bonds that characterize PFAS, transforming them into less toxic or harmless compounds.

The Advanced Reduction Process (ARP) combines reducing agents (ferrous iron, sulphide, sulphite, iodide and dithionite) with activation methods (ultrasound, ultraviolet, microwave irradiation, electron beam) producing highly reactive spices that can degrade contaminants, such as PFAS [40]. In addition, Vellanki et al. observed better degradation for PFOA when they operated with the combination of ultraviolet light with sulphite [41].

The ultrasound process is based on the application of high-frequency ultrasonic waves to break down the molecules. Its application in PFAS, according to Kucharzyk et al. showed that the treatment is favourable and requires a moderate operating cost for energy use, but its large-scale applications would involve a large economic cost [42]. On the contrary, Babu et al. concluded that working on a large scale in a complementary manner with Advanced Oxidation Processes (AOPs) would be more efficient and economically viable [43].

In principle, the AOPs seem to eliminate the compound because they attack the acid group. The problem is that they do not manage to defluorinated the molecule because the C atoms are saturated with F atoms and do not have a C-H bond, so they cannot attack them. As a result, toxic organofluorinated compounds remain in the water.

Chemical oxidation processes use oxidizing agents that react chemically with the pollutants present in the water to break them down or transform them into less toxic products. The most common oxidizing agents are ozone, hydrogen peroxide, and potassium permanganate [44,45,46]. Some oxidants have been shown to be effective in decomposing perfluoroalkyl carboxylates, but perfluoroalkyl sulfonates present considerable challenges to be attacked by oxidation [47].

Electrochemical oxidation is performed by direct and indirect anodic oxidation. In direct electrolysis, contaminants are adsorbed and degraded directly on the electrode. In indirect electrolysis, contaminants are degraded in the bulk liquid by reactions with oxidizing agents formed at the electrode. This technique, although it has several advantages, such as the ability to operate at ambient temperature, without requiring chemicals and without generating waste; it also has its disadvantages, such as the possible existence of environmental risks and certain costs [48].

Photochemical oxidation, which uses electromagnetic radiation, typically ultraviolet (UV) or visible light to generate hydroxyl radicals that break down contaminants, can be useful for treating PFOA. However, it may be less effective than other methods for removing PFAS due to

the strength of the C-F bonds. Hydroxyl radicals may have difficulty breaking these bonds, which limits their effectiveness in removing PFAS. Although photochemical oxidation may be useful in some cases, it is important to consider other treatment options to ensure complete and safe removal of PFAS from water [49-51].

On the other hand, for biological treatment it represents a major challenge since it is necessary to decompose PFAS, which contain extremely strong carbon-fluorine bonds and high negativity of fluorine [36,52].

Existing research presents conflicting results. There is some evidence of biotransformation of PFOA, showing a 30% reduction, using fungi [53,54]. However, in 2019, Turner et al. revealed that using enzymes extracted from Cannabis sativa L. could degrade 98% of PFOS and PFHxS in 1h, unlike results with other microorganisms that require more than 100 days [55].

Plasma treatment plays a crucial role in various industrial applications such as semiconductor manufacturing, polymer functionalization, chemical synthesis and toxic waste management [56,57]. Regarding its use in PFAS degradation, it presents several positive and negative aspects. On the one hand, plasma can effectively remove both short-chain and long-chain PFAS [58]. However, a negative aspect is that short-chain PFAS may require longer treatment times compared to long-chain PFAS [59] and, in addition, studies have confirmed the presence of short-chain PFAS after treatment, such as PFHpA, PFPnA and PFHxA [60].

Plasma technology is relatively new for the treatment of PFAS-contaminated water and is still in an experimental phase. Its main drawbacks are high cost and high energy consumption [35].

In view of these results, there is a clear need for further development and application of efficient and environmentally friendly technologies for the removal of these contaminants from aqueous streams.

2. OBJECTIVES

The general objective of this project is to evaluate the efficiency of the PFAS removal process by aeration. To achieve this general objective, the following specific objectives have been developed:

- Propose the mechanism of PFAS removal from water by aeration.
- Perform a literature review related to the aeration process for PFAS removal from water.
- Analyse the effect of the main factors in the aeration process on PFAS removal from water.
- Establish the most significant variables influencing the PFAS removal efficiency by aeration.

3. METHODOLOGY

To find relevant information on this topic, a search on the two major academic databases was carried out: Web of Science and Scopus. These platforms offer a wide range of peerreviewed scientific articles in various disciplines. Exploring these databases allowed to access a wealth of research and studies relevant to this research.

Firstly, 753 articles were obtained by searching for "removal pfas water" without specifying any particular procedure on March 5th, 2024, on the Web of Science database. This result reflects the interest of the scientific community in the removal of PFAS in the aquatic environment and has been growing last years, as can be seen in, Figure 4, showing the evolution of publications since 2014.



Figure 4. Evolution of "PFAS removal from water" publications.

To carry out this literature review on PFAS removal from water, an exhaustive search was conducted in the Web of Science (WOS) and Scopus databases. First, a pre-reading of documents related to the objectives of the study was carried out to establish the most appropriate terms for searching. Then, the following search strategies were used: (1) "removal

PFAS water aeration" and (2) "removal PFAS water aerosol". The search for these terms was performed in both databases, but with different search methodologies. On the one hand, in Web of Science the search was done in all fields, while in Scopus it was necessary to search in depth using article titles, abstracts and keywords; because searching in all fields yielded 293 and 316 documents for "removal PFAS water aeration" and "removal PFAS water aerosol", respectively.

With this initial search we obtained a total of 34 documents, all of them in English and research articles, of which 18 were from WOS and 16 from Scopus.

First, 15 duplicate articles were eliminated, leaving a total of 19 unique articles. Then, through a detailed analysis of the references of these articles, we identified 14 new relevant articles that had a possible relationship with our search. Thus, the total set of articles increased to 33 documents.

Finally, an exhaustive reading of all the articles was carried out to evaluate their eligibility with established criteria. Articles that did not evaluate the aeration process, articles that used aeration to induce another process such as foaming and adsorption, and finally articles that had another objective without exposing disposal results such as landfill leachate treatment, PFAS transport and soil treatment were separated into three categories.

This process resulted in the elimination of 26 articles that did not meet the inclusion criteria, leaving a total of 7 articles that were finally part of the systematic review.

The following flow chart represents the search methodology procedure.



4. RESULTS AND DISCUSSION

This section includes the results based on the literature search that have been discussed to achieve the objectives proposed above.

4.1. AERATION IN THE REMOVAL OF MICROPOLLUTANTS FROM WATER

The aeration technique is based on introducing air into the water to improve oxygen transfer by increasing the level of dissolved oxygen and thus facilitating the removal of various contaminants. This process is carried out by diffusers that create bubbles or with mechanical agitators that mix the air with the water, as can be seen in Figure 5. It has several mechanisms that contribute to the improvement of water quality and is used in water treatment [61].

Aeration is mainly used in WWTPs because it is determinant for the achievement of aerobic conditions that allow microorganisms to effectively decompose organic matter and reduce pollution.

On the other hand, in DWTPs it is used to eliminate dissolved and volatile gases, such as carbon dioxide and hydrogen sulphide, improving the taste and smell of the water.



Figure 5. Aeration scheme.

4.2. LITERATURE REVIEW ON THE REMOVAL OF PFAS FROM WATER

Table 2 collects the research articles resulted from the literature review focusing on the removal of pfas from water by aeration.

Target PFAS	Studied Process	Operating conditions	Main results	Ref.
PFOA	Gas-phase-PFOA Aerosol from water	[PFOA]₀ = 205-797 µg/L. pH₀: 5.72-8.22 Atmospheric T=18.7-22.6 °C Water T =20-30 °C Relative humidity = 83.3-99.9% Different types of matrices: DI water; lake water; river water; filtered river water; ocean water.	Aerosols contained significantly higher concentrations of PFOA than the original water body, being up to 80 times higher in ocean waters.	[64]
PFAS PFCAS(C6-C14) PFSAs (C6, C10, C14)	The water-to-air transfer Gas- phase Sea spray simulator containing tap water spiked with PFCAs and PFSAs	Initial mass in the system PFAS :881-1682 ng Bulk water concentration after 16 h PFAS: 0.4-13.6 ng/L	The capture of PFAS from bulk water to the air-water interface was shown to significantly increase with the length of the perfluorinated alkyl chain. Volatilization of the PFAAs from an aqueous solution in the absence of spray was in less than 1 %. However, in the presence of spray, the transfer rate from water to air increased by up to 1360 times.	[65]

Table 2. Studies included in the literature review

PFAs	Gas-Phase PFAS generation of gas bubbles in solution, enrichment and scavenging of fluorosurfactants by transport of the gas bubbles to the water surface.	mass balance was established for 6:2 fluorotelomer sulfonic acid (6:2 FTSA) Parameters of wastewater. pH:1.9-8.6 6:2 FTSA: 2.9-8.5 mg/L Conductivity :9.2-22.3 mS/cm Investigated in different aqueous matrices.	The aerosol-based separation could be successfully achieved to surfactants with a higher carbon chain length. 99.6% for 6:2 FTSA, 99.9% for PFOA and 99.8% for PFOS in defined matrix and half- lives were between 2 and 6 min.	[66]
PFOS	Aeration and foam collection to remove PFOS from a commercially available AFFF solution	[PFOS] = 46,512 -191,049 μg/L. Air flow rate= 50-125 mL/min Ionic strength: [NaCI]=0.1-5 mmol/L pH ₀ = 3, 6,10 (adjusting with NaOH or HCI)	Increasing the aeration flow rate, ionic strength, concentration of co-existing surfactant, and decreasing the initial PFOS concentration all led to higher removal percentages of PFOS by increasing the foam volume but reduced the enrichment of PFOS in the foams. PFOS removal reached 96% within 2 hours using an aeration flow rate of 75 mL/min. High ionic strength accelerated PFOS removal via aeration-foam collection. Aeration-foam collection is suitable for PFOS recovery from AFFF wastewater.	[67]

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8 PFAS PFBA PFPeA PFBS PFHxA PFHpA PFHxS PFOA PFOS	Aeration to remove PFAS from aqueous solutions and duckweed	Eight PFAS were spiked to either deionized water or Hoagland solution pH ₀ =2.3-7.5. Experiment with/without duckweeds and with/without Air bubbling [PFAS]:2-200 µg/L	Best removal rates were with PFHpA, PFHxS, PFOA and PFOS Aeration in deionized water for 7 hours at pH 2.3 removed 80% of PFOS and PFOA at 200 µg/L Salts, compared to water, resulted in higher removal of long-chain PFAS at 2 µg/L at all pH levels. Duckweed treatment resulted in over 95% removal of long-chain PFAS at 200 µg/L after 2 weeks. Duckweed accumulated 14.4% of the spiked PFOS in 2 weeks.	[68]
30 PFAS	Removal of PFAS Species from Water by Aeration in the Absence of Additional Surfactants	The effect of temperature, and aeration time on PFAS removal from contaminated waters $T^{\circ}C:4.3-37.1$ The effect of salinity on PFAS removal was determined using different additions of analytical grade of NaCl in a solution of RO water spiked with 3 M Lightwater to a target concentration of 5 µg/L of Σ PFAS (n = 30).	The bubble fractionation process can effectively operate over a broad range of salinity and temperature conditions, achieving high levels of overall PFAS removal (>95%). Short-chain PFAS species, characterized by lower air-water adsorption coefficients, were enhanced by both increased electrolyte (i.e., salt) concentrations and decreased temperature in treated water. Total PFAS removal decreased slightly (to 93%) when processing higher temperature (37°C) feedwater.	[69]

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PFAS	Gas-Phase PFOS Aerosol remove PFOS from a WWTP if aerosols generated during aeration	the wastewater was spiked with 6:2 FTS, PFBA, FHxA, PFOA, PFBS, PFHxS, and PFOS to achieve a final concentration of approximately 1000 ng/L each. Air flow rate= 20 - 60 mL/min Distance = 2.5 - 34 cm	Removal effectiveness was notably higher for PFAS with longer chains and high surface activity. PFAS removal typically improved with better aerosol capture and increased aeration. 75% of PFOS was successfully removed from wastewater. Increasing the aeration rate threefold resulted in a 97% removal of PFOS.	[70]
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4.3. PROPOSAL OF THE PFAS AERATION MECHANISM

Aeration is presented as a promising technique for the removal of PFAS in water and the mechanism of this process has been first investigated in this paper.

In this regard, one of the first articles that began to investigate the global distribution mechanisms of PFAS was published in 2008 by Kutsuna and Hori. In it, they analysed the Henry's law constant (Kh) of PFOA at 298 K in aqueous sulfuric acid solutions and in aqueous mixtures of sodium chloride and sulfuric acid by an inert gas stripping method in which a helical plate was used to increase the residence time of gas bubbles in the solutions. The Kh values of PFOA were 9.9 ± 1.5 mol /dm³atm and 5.0 ± 0.2 mol /dm³atm for pKa values 2.8 and 1.3, respectively. They concluded that the pKa of 1.3 seems to be the most likely among the values reported for PFOA, considering the dependence of Kh' on sulfuric acid concentrations in aqueous mixtures of sodium chloride and sulfuric acid [62]. Although the objective of the study was not focused on the removal of PFOA, the means to fulfil the objectives of the work was, based on the volatilization of this compound from the aqueous medium.

On the other hand, in 2013, Vierke et al. conducted a study to try to better constrain the pKas of perfluorocarboxylic acids (PFCA) with an experimental investigation of their water-air transport behaviour at concentrations (\sim 1 µg/L) above ambient concentrations, but below the limit at which self-association into micelles or aggregates occurs and at different water pH ranges.

For PFCA to be transferred in its gaseous form in water to air, the pH of the water must be near or below the pKa of the compound, which is why experiments were performed at different pHs to assess its volatilization.

In the experiments they worked with several compounds: perfluorobutanoic acid (PFBA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), PFOA, perfluoronononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA) and perfluorododecanoic acid (PFDoDA). Other compounds were also tested for comparison, such as perfluorobutane sulfonate (PFBS), perfluorohexane sulfonate (PFHxS), perfluorooctane sulfonate (PFOS) and 8:2 FTUCA.

The results showed that the pKas of PFCAs with C4-11 carbon atoms were less than 1.6. Furthermore, fitting the experimental measurements with a volatilization model, a pKa of 0.5 was obtained for PFOA. However, perfluoroalkane sulfonic acids (PFSAs) did not volatilize, suggesting that their pKas are below the investigated pH range (pKa < 0.3) [63].

Although in the previously mentioned studies the objective was not to know the mechanism of removal of PFAS from water and their transfer to air, they represent a first advance in describing their ability to volatilize Figure 6 shows the experiment of the volatilization of these compounds and their behaviour depending on the pKa of the substance and the pH of the water.



Figure 6. Mechanism volatilization adapted from Vierke et al [63].

On the other hand, all the articles in this literature review, shown in Table 2, are based on another mechanism of elimination, the formation of aerosols. Therefore, both seem to influence the PFAS elimination process.

In this second mechanism, one of the main characteristics of these compounds must be considered. PFAS have a structure that includes a hydrophobic part, which is water repellent, and a hydrophilic part, which is soluble in water. This characteristic allows them to behave as surfactants, i.e. they tend to accumulate at the interfaces between water and air. PFAS accumulate on the surface of the bubbles because their hydrophobic parts seek to move away from the water and their hydrophilic parts interact with the aqueous phase. Therefore, when air

bubbles are introduced into the water, in the aqueous medium the hydrophobic part is towards the air bubble, as can be seen in Figure 7. However, when the air bubbles reach the surface, they are transported to the air in the form of aerosols, liquid particles, in which their position is reversed, with the hydrophobic part of the molecule remaining towards the outside.



Figure 7. Mechanism for aerosol formation. (Source Ebersbach et al. [66])

4.4. EFFECT OF PARAMETERS ON PFAS AERATION.

4.4.1. Study of the initial concentration in PFAS aeration.

The range of the influence of the initial concentrations was studied in a very wide interval. The initial concentration of PFAS can influence the efficiency of this process because depending on the characteristics of the water they can be found in higher or lower concentrations.

As a result, different studies have worked operating in different concentration ranges from 205 μ g/L up to about 200000 μ g/L, practically 1000 times more, and some of them have even evaluated the influence of this parameter.

One of the first works found in the literature in this field was carried out in 2008 by Mcmurdo et al. in which they specifically studied the compound PFOA, in its anionic form as perfluorooctanoate (PFO), considering that most of the compound (>99%) would be found in its ionized form in the environment. In this study at real concentrations of this compound in different matrices, such as deionized water, rivers, lakes and oceans; they evaluated the amount of the compound that was enriched in the aerosol, separating from the water.

With an initial PFO concentration of 205-797 μ g/L after enrichment with PFO, they performed pH measurements before, 5.72-8.42, and after, 5.71-8.45, the procedure in the different matrices. The results showed aerosol enrichment factors (EF) ranging from 4.4 (filtered river water) to 55.7 (ocean water). This difference is due to the large amount of salt in the water, the ocean water having a higher ionic strength which causes an increase in the hydrophobicity of the hydrophobic fraction of the PFO anion. They also evaluated the residence time of PFO in the generated aerosol droplets obtaining a mean value of 7.2s, for the case of filtered river water, indicating that the generation of aerosols is a highly effective process for the PFO present in the water to be transferred to the atmosphere in the form of gaseous PFOA. They found that the aerosols contained PFO concentrations significantly higher than those in the original water mass, being up to 80 times higher in oceanic waters [64].

More recently, Zang and Liang in 2020, studied only in two ranges the influence of the concentration of different PFAS, at 2 and 200 μ g/L. The research was conducted in two different matrices, in deionized water and in Hoagland's solution, which is a plant nutrient solution developed by botanical scientist Dennis Robert Hoagland in the 1930s and, therefore, the concentration of salts and minerals is significantly higher than in deionized water.

The results reflected that in Hoagland's solution, the removal of PFOA, PFHxS and PFHpA at a concentration of 2 µg/L was higher than at 200 µg/L. In contrast, in deionized water, the removal of PFHxS and PFOS at 2 µg/L was significantly lower than at 200 µg/L. They did not obtain precise conclusions about their influence [68].

In contrast, in another study conducted by Mentg et al. in 2018 they studied that aeration could result in both aerosol and foam formation. That is why, they combined foam collection with aeration and studied its effect in a higher concentration range of 46512 µg/L up to 191049 µg/L and observed that PFOS removal percentages decreased with increasing initial concentrations, 99.38% and 96.07% respectively [67].

Delving further into foam formation, a 2016 publication by Ebersbach et al. stands out in which they analysed compound 6:2 FTSA in a system with pore diameter of 16-40 μ m, with a matrix solution of 0.2 M H₂SO₄ and a gas flow rate of 7 mL/min cm².

In this study, they evaluated the influence of concentrations working in the range of 10 μ g/L to 19200 μ g/L shown in Table 3. They found that when exceeding a critical threshold, the aerosol removal rate decreased considerably due to the formation of foams [66], attributing that it could be due to the presence of foam sheets that can prevent the release of aerosols.

It should be noted that as previously mentioned these high PFAS concentration values would not be found in real waters.

Table 3. Evaluation of initial concentrations in the removal of pfas from water with aeration.

C initial		
6:2 FTSA	Elimination	Foam
(µg/L)	(%)	
10	>99	no
130	>99	no
200	>99	no
5000	>99	no
16600	16	yes
19200	36	yes

(Source Ebersbach et al. [66])

In general, when operating at very low concentrations, PFAS can be removed very effectively, but when a concentration value is exceeded, as specified by Ebersbach et al., foams are formed, and removal is not as efficient.

4.4.2. Study of pH in PFAS aeration.

Another parameter that is relevant in water treatment is the influence of the pH of the aqueous medium.

In this sense, in the works included in this literature review, this parameter was studied in a range of 2.3 to 10. The pH of real waters can usually be found in a range of 6.5 to 8.5 and water treatment processes can be influenced by the pH of the medium in which they are found, therefore, it is a parameter that is of interest to study.

In 2020, Zhang and Liang analysed the influence of pH in a range of 2.3 and 7.5 and observed that as pH increased the removal rate decreased, but with very little difference. They associate the little effect to the fact that the pH range they studied was much higher than the pKa [68]. In general, PFAS have rather low pKas, which means that they are strong acids. Their values usually vary between -3 and 3, depending on the type of functional group the molecule has. There are several studies that analyse the importance of the pKa of PFAS substances,

such as Vierke et al. in 2013 who analysed the pKa value of PFCAs to study their degree of PFCA volatilization in the environment as it will depend on the pH of the water and the pKa of the compound [63].

Zhang and Liang concluded that when pH is reduced, regardless of PFAS concentrations or the presence of Hoagland salts, the removal rates generally increased [68].

Likewise, Meng et al. analysed the influence of pH on PFAS removal, in 3 ranges, adjusting its value by using HCI and NaOH to 3, 6 or 10 and observed that both acidic (98.98%) and basic (99.80%) solutions had higher removal rates than neutral solution (96.07%). The slight difference in the percentage between acidic and basic solutions is because in the case of the acidic solution its stability is decreased by the excessive presence of hydrogen ions that can neutralize the negative charges of the air bubbles [67].

In conclusion, the studies analysed do not detect significant changes with the effect of pH with the elimination of PFAS. This process is very versatile and further analysis with larger ranges would be necessary to determine a more accurate result.

4.4.3. Study of chain length in PFAS aeration.

There are currently many different types of PFAS compounds and their degree of influence on the process also depends on their chain, particularly their length. Short-chain PFAS are less hydrophobic than long-chain PFAS, which makes them more soluble in water. This greater solubility makes them more difficult to remove by certain treatment methods that are more effective for hydrophobic compounds. This is why short-chain PFAS tend to be more prevalent in water [71,72]. Therefore, it is important to know if this process is equally efficient for all of them, which is why this parameter has been considered in this study.

Reth et al. studied at laboratory scale, the transfer of these compounds in a sea spray simulator resembling the natural procedure of breaking waves that would expel them from the water.

With PFCA and PFSA enriched tap water, they performed two experiments, in the absence and in the presence of the spraying procedure. They measured the initial amount in the system (ng) in both experiments, but the difference between them was negligible. For the first case, it was found that for all PFAS, less than 1% of the amount initially present in the system was transferred to the air. This suggests that PFAS gradually evaporate into water. In the second experiment they observed a large difference of the transfer to the filter in the system and made that comparison in the form of mass ratio in the filter with and without sprayer being, 37, for PFHxA and 1360, for PFNA.

Reth et all confirmed that the amount transferred increased with the chain length of PAS, ranging from 48% to 67% transfer to the filter. This study demonstrates that the aerosol formation effect can transport PFAS from water to air effectively, and that this efficiency increases with the chain length of the molecule [65].

In the same way, Ebersbach studied how the percentage of removal varied for different fluorosurfactants, PFSA, PFCA and 6:2 FTSA, analysing for 60 min with an initial concentration of each of 2 mg/L, a pore diameter of 16-40mm, in a 0.2M H₂SO₄ matrix solution and with an air flow of 5mL/ (min cm²). They found that the removal rate was optimal for compounds with a carbon chain \geq C7, 99.96% for PFOS and 99.82% for PFOA, on the other hand for short chain PFAS could not be removed with a good removal rate within 60 min due to their lower surface activity [66]. Figure 8 shows the main results reported in this work.



Figure 8. Chain length effect. (Source Ebersbach et al. [66])

Also, Zhang and Liang worked with 8 different PFAS and found that there was a positive correlation with the length of the fluorinated carbons with the removal efficiency. For both carboxylic and sulfonic acids, the number of fluorinated carbons required to obtain a significant removal rate was ≥ 6 .

They further found that the affectivity to aquatic plant uptake of PFAS did not affect either aeration or concentrations, but, in contrast, carbon chain length did influence. In Hoagland's solution they obtained a >95% removal rate of long-chain PFAS (PFHpA, PFHxS, PFOA and PFOS) at 200 μ g/L after 2 weeks. They concluded that, with increasing chain length, the ability to absorb PFAS from water increased [68].

The influence of the chain length of the fluorinated compound was studied in several articles and most of them conclude that as the number of carbons increases, the efficiency of their transport and/or removal increases.

4.4.4. Study of ionic strength in PFAS aeration.

In real waters there are different amounts of salt and that is why the ionic strength is a parameter that has been considered in this analysis because depending on the greater its interaction it can influence the solubility of the compound to a greater extent.

Ebersbach et al. worked in their experiments with an initial 6:2 FTSA concentration of 7.5 mg/L, system pore size of 16-40 mm and an air flow of 5 mL/ (min cm²) and varying in different solutions the ionic strength in the range of 0.002-0.2 M Na₂SO₄. They observed that the lifetimes, which indicate the period it takes to reduce the concentration of PFAS in this process, decreased as the presence of salts increased as can be seen in Figure 9.

A possible explanation is that a higher salt content results in a reduction of solubility, thus proving the influence of ionic strength on the removal of these fluorinated compounds [66]. However, this would be in discrepancy with what was found in the previous parameter since the long-chain ones that were less soluble were eliminated more, therefore an investigation comparing their influences in parallel would be necessary to reach a more precise conclusion.



Meng et al. analysed the influence of ionic strength by adding 0, 0.1 or 5 mmol/L NaCl in PFOS solution. They observed that increasing the salt content increased the removal rate up to a certain point and then remained stable. Overall, high ionic strength was beneficial for PFOS removal by the foam aeration-collection process [67].

Zhang and Liang worked with deionized water (0 mmol/L) or Hoagland solution (31.3 mmol/L) to test its effect. PFHpA, PFHxS, PFOA and PFOS had the best results. When they were under the same conditions, they obtained that with a higher amount of salt (Hoagland's solution) had better removal efficiency at 2 μ g/L than at 200 μ g/L. Among the four PFAS, PFOA and PFOS, had the highest removal rate, about 80 % in deionized water at 200 μ g/L [68].

Morrison et al. worked with 4 different NaCl addition levels in water solutions previously purified by reverse osmosis. The mean concentration analysed after addition was $4.07-4.48 \mu g/l$; they also measured the pH, 6.5-6.9, slightly acidic.

They obtained that after 20 min of aeration they had a considerable elimination of PFOS, PFOA and PFHxS compounds and a practically total elimination after 60 min of PFDS, PFHpS, PFHpA and PFNS. The study confirmed that working with higher salinity levels in the treated water increased the efficacy and removal rate of PFAS [69].

In conclusion, most studies confirm that when there is a higher ionic strength the removal rates are better in the analysed matrices, although it is necessary to highlight that in Zhang and Liang research in which he worked on two matrices, their results were better in deionized water in which the amount of salt was significantly lower than in Hoagland's solution.

4.4.5. Study of air flow in PFAS aeration.

As for the aeration flow rate, it is not a parameter that has been studied in depth in most of the articles reviewed, even so it has been considered in this analysis because it may be interesting to check whether or not it influences this process for the removal of PFAS.

Ebersbach et all., only analysed two flow rates, 3 and 15 mL/ (min cm²) in a system with a pore diameter of 16-40 μ m, a matrix solution of 0.2 M H₂SO₄ and an initial concentration of 5 mg/L. Their results had no significant difference in the removal rate [66]. A possible explanation may be that the range studied was too small to reflect a considerable change.

Meng et al., in assessing the effect of the amount of aeration, observed that they had to reach an equilibrium because with flow rates of 100 mL/min and 125 mL/min they obtained 99% PFOS removal in 100 min and 50 min, but this led to an increase in the PFOS removal rate. However, this led to an increase in the foam and consequently a decrease in the PFOS collection in the foam, therefore, they found that the optimal result was to work with a flow rate of 75 mL/min obtaining a percentage of 96% of PFOS after 2h and with a concentration in the foam of 6.5 mmol/L [67].

Recently, Nguyen et al. studied the ability of using a sorbent material to collect PFAScontaining aerosols emitted from a WWTP for subsequent removal.

They observed that varying the aeration rate from 20 mL/min to 60 mL/min both working at the same distance from the water surface to the sorbent material of 2.5 cm removed 75% of PFOS compared to 97% when working at the higher ratio. PFAS mass removal achieved in 180 min with the lower aeration rate was achieved in half the time with the higher aeration rate [70].

They also confirmed the hypothesis of the influence on the chain length of the fluorinated compound, with long chain having better removal rates relative to short chain.

Table 4. Evaluation of air flow in the removal of pfas from water with aeration.

Experiments	Aeration rate	Distance from top of reactor
	(mL/min)	(cm)
1	20	34
2	20	2.5
3	60	2.5
4	20	5.1
5	20	10.1

(Source Nguyen et al. [70])

Two studies conclude that, in comparison, working with higher flow rates results in a better PFAS removal rate. It can be observed that the only article that did not prove a considerable change in its results analysed a lower flow rate range compared to the two studies that did see the influence of this parameter. Further research with a wider range of flow rates would be necessary to confirm this assumption.

4.4.6. Study of other parameters in PFAS aeration.

On the other hand, there are other parameters that have not been analysed in depth, such as temperature and coexistence of substances, but they could influence the removal efficiency.

The effect of temperature was only considered by Morrison et al. with two extreme cases 4.3°C and 37°C. Working at room temperature ranging from 21-23°C and the average concentration of the fluorinated compounds was between 2.84-4.48 µg/L. They showed that the removal rates were higher when operating at lower temperatures for long chain compounds (PFOS, PFOA and PFHxS) and for some short chain compounds (PFBS, PFHxA and PFPeS) [69].

Meng et al. studied how the coexistence of other substances influenced the PFOS removal process. In this case, they chose N-Octyl-β-D-glucopyranoside to represent typical components of typical APGs. APGs are a class of non-ionic hydrocarbon surfactants commonly used in the AFFF industry. The surfactants can decrease surface tension and increase the stability of air bubbles in solution and favoured PFOS removal by increasing foaming as can be seen in Figure 10 [67].



4.4.7. Comparison of the most influential parameters in PFAS aeration.

Once these parameters have been analysed individually, it is important to know their degree of influence on the elimination of PFAS. In this regard, only one of the most recent investigations compiled in this literature review slightly analyses the influence of several parameters. Three factors, salts in the Hoagland solution (ionic strength), PFAS concentrations and pH, and the possible interactions between them are analysed. Zhang and Liang concluded that, for PFOS, initial concentrations and pH were significant factors in their removal. On the other hand, the interactions of Hoagland salts-pH and initial concentrations-pH were relevant for the removal of PFHpA and PFOA. And, likewise, the Hoagland salts-initial concentrations relationship was very important for the removal of long-chain PFAS [68].

Finalizing this analysis of the most influential parameters in the aeration process for PFAS removal from water, Figure 11 shows the classification of the effects reported in this literature review in a more visual and direct way. The colours represent their contribution to the efficacy, with green being the most effective, blue intermediate and red the least effective. The white colour, on the other hand, indicates the range that has not been possible to conclude because there is no conformity in the results presented, as is the case of the effect of pH.



Figure 11. Classification of the effects at different ranges

Finally, this paper concludes with several recommendations for future research on PFAS removal by aeration. Although the aeration process is a conventional process in water treatment, it is a technology that has been scarcely investigated so far for PFAS removal. In this project, the state of the art has been synthesized and collected, and the removal mechanisms have been proposed. Nevertheless, the following recommendations are proposed to further investigate this technology and the influence of the different parameters such as the evaluation of:

- Effect of pH: no conclusive conclusions have been obtained regarding its influence.
- Effect of the nature of PFAS: in the functional group of these substances could have an important role in terms of their influence on their elimination.
- Complex real matrices: these substances are found in nature together with other compounds, contaminants and in complex matrices that can significantly influence their elimination.
- Collection methods in the air: once the PFAS are transported into the air if it is by aerosol formation it is recommended to deepen the subsequent treatment of the same and for this purpose it is necessary to collect them by evaluating different media (filter paper, plants, adsorbents...).
- Subsequent treatment: If the removal mechanism is by volatilization, air decontamination treatment would be necessary, while if it is by aerosols, once collected, it would be necessary to treat this concentrated aqueous medium.

5. CONCLUSIONS

In this Project, the evaluation of the aeration process for the elimination of PFAS from water has been carried out, obtaining the following main conclusions:

- In the literature review, 7 articles were obtained, a relatively small number due to the novelty of the PFAS application of the aeration process.
- The mechanisms for removing PFAS from water that have been proposed in the literature are stripping (volatilization) and the formation of aerosols by aeration.
- At very low concentrations PFAS can be removed very effectively, however, when a certain value is exceeded, foams are formed, and removal is not as efficient.
- When the chain length of the compound is greater, the efficiency of its transport and/or elimination increases.
- In general, the higher the ionic strength, the higher the removal rates in the matrices analysed, however, there is some discrepancy.
- When operating at higher air flow rates, a higher PFAS removal rate is obtained.
- The variables contributing most to the removal efficiency were initial concentration, chain length and air flow rate.

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