

Review

An Overview of Treatments for Ultraviolet Quenching Substances (UVQS) and Per- and Polyfluoroalkyl Substances (PFAS) Removal from Landfill Leachate

M^a Carmen Márquez *

Department of Chemical Engineering, Faculty of Chemical Sciences, University of Salamanca, Plaza de los Caídos 1-5, 37008-Salamanca, Spain; E-Mail: mcm@usal.es

* **Correspondence:** M^a Carmen Márquez; E-Mail: mcm@usal.es

Academic Editor: Luisa Barbieri

Special Issue: [Advances in Treatment of Leachate from Solid Wastes](#)

Recent Progress in Materials
2024, volume 6, issue 1
doi:10.21926/rpm.2401002

Received: September 15, 2023
Accepted: January 04, 2024
Published: January 24, 2024

Abstract

Organics found in landfill leachate (humic acids, fulvic acids, and hydrophilic fraction) have a solid ability to absorb ultraviolet (UV) radiation, which negatively affects UV disinfection; leachate ultraviolet quenching substances (UVQS) can, therefore, have a significant impact on the cotreatment of landfill leachate and sewage in wastewater treatment plants. On the other hand, per- and polyfluoroalkyl substances (PFAS), which pose potential risks to the environment and human health, commonly exist in landfill leachate due to their wide application in various industrial and consumer products. Therefore, removing UVQS and PFAS from landfill leachate is crucial. In this work, the advances in removing UVQS and PFAS from landfill leachate in the last decade are reviewed to find a standard treatment for both contaminants to lower the costs and space required for the leachate treatment process. The benefits and drawbacks of biological, physical, chemical, and electrochemical treatments were examined. Physical, chemical, and electrochemical treatments showed advantages over biological treatments but higher energy and/or material costs. The global analysis indicated that similar technologies, such as adsorption or osmosis, can be used as effective methods to remove UVQS and PFAS from landfill leachate and suggested that both types of pollutants



© 2024 by the author. This is an open access article distributed under the conditions of the [Creative Commons by Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium or format, provided the original work is correctly cited.

could be eliminated simultaneously with a single treatment based on one of these two technologies.

Keywords

Ultraviolet quenching substances; per- and poly-fluoroalkyl substances; landfill leachate; removal technologies

1. Introduction

The evolution of society has currently reached a life model based on a constant increase in consumption whose immediate consequence is the generation of a series of solid wastes that can harm the environment [1]. Although the generation of waste by man has always existed, for a long time, the waste of animals and plants contributed to the support of the life of the ecosystems. However, the constant increase in their generation rates has caused, in many cases, a breakdown of the balance between the biosphere and human activities [2]. Waste generation rates are increasing drastically. Factors such as population growth, urbanization, economic growth, and consumer shopping habits determine this increase [3]. In 2020, the globe produced 2.24 billion tonnes of municipal solid waste (MSW); in 2050, global waste generation is expected to grow to 3.88 billion tonnes per year, a 73% increase compared to 2020 levels [3].

The increasing generation of MSW has become a significant burden to society because of the serious environmental and economic problems during waste disposal. Compared with other technologies, such as composting or incineration, landfilling is a relatively convenient, inexpensive, and widely employed method for MSW management [4].

MSW disposal in landfills involves some risk since solid waste will be exposed to degradation, further releasing hazardous constituents to the environment. Although modern landfills are highly engineered facilities designed to suppress or diminish the adverse impact of waste, producing leachates remains a severe problem for MSW landfills because these leachates constitute a significant danger to soil, surface water, and groundwater [5].

Leachate is produced from waste degradation and rain penetration through the landfill [6]. It results from two main processes occurring in a landfill: 1) water percolation in the dumped waste mass and 2) mass transfer of chemicals from waste to percolating water [7].

Pollutants in municipal landfill leachate are toxic organic and inorganic compounds, including microorganisms [8, 9]. The most common specific categories of pollutants found in leachates include dissolved organic matter, trace ions, xenobiotic organics such as polychlorinated biphenyls or pesticides, and ammonia [10, 11]. However, leachates can also release heavy metals, polychlorinated organic compounds, and emerging contaminants into the ecosystem [12-14]. Therefore, leachate collection and treatment are essential to avoid the environmental pollution from landfills [15, 16].

Although some landfills use leachate pre-treatment before discharge, and others provide leachate treatment prior to permitted discharge to the environment, most leachate is sent directly to wastewater treatment plants for treatment. Although leachate cotreatment with municipal wastewater can remove significant amounts of pollutants (e.g., organic matter, nitrogen,

phosphorus) [17], this treatment is being hampered by emerging contaminants and strict regulations [18].

Emerging contaminants such as ultraviolet quenching substances (UVQS), per- and poly-fluoroalkyl substances (PFAS), microplastics (MP), antibiotics (A), endocrine-disrupting chemicals (EDC), or antibiotic resistance genes (ARG) [13, 19-22], have made it challenging to use traditional wastewater treatment methods (primary and secondary wastewater treatments). These pollutants are becoming more concerning due to their co-occurrence and impact on overall treatment effectiveness [14]. This problem implies the need for action by wastewater treatment plants and landfills for enhanced emerging contaminant removal or treatment [23].

Among emerging contaminants, at present, UVQS and PFAS are the most concerning leachate pollutants because the presence of UVQS in the final effluent after biological treatment that hampers ultraviolet (UV) removal of pathogens in subsequent disinfection processes [24] and the dominance of PFAS (dangerous for human health and the environment) in leachate compared to wastewater and freshwater [14].

Although there are many studies on eliminating UVQS or PFAS from landfill leachate, none have evaluated the possible existence of a standard treatment for both contaminants. Consequently, it is crucial to explore the UVQS and PFASs removal from landfill leachate through advanced remedial measures to find a standard therapy for both pollutants, reducing leachate treatment costs and space. Therefore, this research aims to document the existence or absence of common treatments for UVQS and PFAS removal from landfill leachate. For this purpose, this paper reviews the latest potential technologies for UVQS and PFAS elimination from landfill leachate. It discusses the advantages and disadvantages of these methods for treating landfill leachate. In this context, the study has four specific objectives: to characterize the landfill leachate in terms of UVQS and PFAS, to review the recent technologies of UVQS removal from landfill leachate, to review the new technologies PFAS removal from landfill leachate, and to use the information obtained in previous objectives to determine a possible treatment for simultaneous removal of UVQS and PFAS from landfill leachate.

2. Leachate Characteristics

Landfill leachate is a complex wastewater with considerable variations in composition and volumetric flow [25].

The physical-chemical characteristics of leachate depend on a series of factors such as [4]:

- Nature, composition, and total volume of stored waste
- Landfill age, design, and operational practice
- Hydrogeology, climatic conditions, and seasonal weather changes.

Among these factors, the landfill age becomes the critical factor in determining the leachate composition once the leachate is collected in the leachate collection pond [26, 27]. Based on the landfill age, leachates are classified as young, intermediate, and old [28]. Young leachates are those that come from landfills less than 5 years old, where the aerobic and acidic stages prevail, and biodegradability is essential; the pH is ~6.5; carboxylic acids constitute more than 80% of the organic compounds; the biodegradable (as biochemical oxygen demand, BOD) and total organic matter (as chemical oxygen demand, COD) are above 2000 and 10000 mg/L, respectively. The BOD/COD ratio is above 0.3 [28]. Old leachates are those from facilities that are more than 10 years old, generated

during the maturation phase; they are mainly composed of a refractory mixture of UVQS (mainly humic acids and fulvic acids) with pH higher than 7.5, COD below 4000 mg/L, BOD below 150 mg/L and BOD/COD ratio below 0.1 [28]. Intermediate leachates are generated in landfills of 5 to 10 years old, and so in the methanogenic phase, and show intermediate characteristics between those of the young and old leachates [28].

Age-related progressive alteration of humic compounds in leachates is mainly responsible for their heterogeneity and difficulty in characterization. In young leachate, fulvic acids are produced first, their concentration higher than that of humic acids. Still, with humification, humic acid concentration rises over time and finally falls as landfills stabilize and natural dilution or degradation occurs [19]. Humic compounds are frequently viewed as the byproducts of the oxidative and biodegradative pathways due to the prolonged exposure of the precursors to water, oxygen, and sunshine; because of this, humic compounds are regarded as "old molecules" resistant to further biological processing but vulnerable to other specific treatments such as advanced oxidation [19]. The concentration of UVQS (consisting of humic acids, fulvic acids, and hydrophilic fraction) in landfill leachate can range from tens to tens of thousands of mg/L, and it is significantly higher than UVQS concentration in freshwater or municipal wastewater (Table 1). PFAS in leachate derived from environmental and consumer products deposited in landfills (such as electronics, cosmetics, cleaning products, dental floss, water-repellent fabrics, carpets, food packaging materials, non-stick cookware, upholstery...) [29-31] can cause adverse biological effects in animals and humans [32], and are reportedly extremely difficult to degrade [13]. The amounts of PFAS in landfill leachates are exceptionally high when compared to the concentration of PFAS found in other liquid matrices such as freshwater or municipal wastewater (Table 1). The reported total PFAS contents in raw leachates ranged from a few to tens of thousands of ng/L (Table 1). The wide range of concentrations of PFAS in leachate is linked to factors such as the kind of waste, landfill management, and treatment practices [29, 33].

Table 1 Concentration of the different categories of UVQS and PFAS in landfill leachate, municipal wastewater, and freshwater.

Compound	Landfill leachate	Municipal wastewater	Fresh water	References
UVQS (mg/L)				
Humic Acids (HA)	16-8800	11-96	0-20	[19, 34-38]
Fulvic Acids (FA)	56-14400	14-133	0-34	[19, 34, 35, 37, 38]
Hydrophilic fraction (HPI)	199-14020		0-14.5	[19, 35, 39]
PFAS (ng/L)				
Perfluoroalkyl carboxylates (PFCA)	35-24,413	10-980	5-970	[14, 40-46]
Perfluoroalkane sulfonates (PFSA)	30-13,269	5-965	4-960	[14, 40-46]
Perfluorooctane sulfonamide (PFOSA)	1-46	2-25	0-44	[14, 40-46]

3. Ultraviolet Quenching Substances (UVQS) Removal

Some refractory organic compounds in landfill leachate with UV quenching characteristics (UVQS) decrease the UV transmittance of wastewater and, hence, can interfere with ultraviolet disinfection when landfill leachate is co-treated with municipal sewage [47]. Ultraviolet quenching

substances (UVQS) are divided into three categories: humic acids (HA), fulvic acids (FA), and hydrophilic fraction (HPI), each of which has specific characteristics and behaviors during the treatments [47]. HA, FA, and HPI concentrations in landfill leachate appear in Table 1.

In the last decade, different technologies have been used to deal with UVQS: biological, physical, chemical, and electrochemical treatments. However, biological treatment is less effective than the other alternatives [48].

3.1 Biological Treatments

The efficiency of biological treatments for landfill leachate depends mainly on the nature and composition of the leachate [49] and can be carried out in either aerobic or anaerobic reactors.

Aerobic biological treatment mainly comprises fixed film and activated sludge bioreactors [19]. After aerobic biological treatment, the decline in UV absorbance and UVQS can range from 2.5 to 55% and 26-60%, respectively [19]. Following biological therapies, the average reduction in HA, FA, and HPI concentrations was 50.2, 53.9%, and 50.1%, respectively [19]; the elimination of UV absorbance for the corresponding fractions was 43.5, 23.5%, and 19.5% [19]. Biological treatment is probably less effective at lowering UV absorbance than total organic carbon due to its ineffectiveness for recalcitrant organic compounds (mainly humic substances) [19].

Organics and UV absorbance can only be removed to a limited extent by anaerobic biological treatment of leachate. For instance, a two-stage anaerobic membrane bioreactor removed 39% of the HA, 37% of the FA, and 55% of the HPI fraction from a landfill leachate, while the reduction of UV absorbance was 46% [50].

Because independent biological treatments are ineffective for removing UVQS, combinations of biological and physicochemical therapies have been researched. For example, leachate blended with sewage and treated by nanofiltration after biological treatment increased the UV transmittance from 35% to 62% when leachate represents 5% of the overall volumetric flow [51]. When powdered activated carbon was added to an activated sludge process, HA, FA, and HPI removal increased from 27% to 53.1%, 40% to 44.2%, and 59.8% to 59.8%, respectively [51].

3.2 Physical Treatments

Most physical treatments use sorption and membrane separation-based methods. Physical treatments typically remove between 23 and 97% of the UV absorbance and between 34 and 98% of the UVQS [19]. These treatments have the advantage that the removed UVQS are not destroyed but separated and can be recovered.

Among the sorption-based methods, HA with a molecular weight range of 0.5-2 kDa and FA with a molecular weight range of 1-3 kDa were preferentially absorbed by carbon nanotubes [52]. Iron oxide coated may also effectively remove UVQS; for instance, using an amount of 40 g/L for 6 hours, it was possible to remove 89.1% UV absorbance and 65.5% UVQS from leachate that had been treated by a microbial fuel cell [53]. Powdered activated carbon reduced UV absorbance by 92%, showing preferential adsorption by the hydrophobic fraction (HA and FA) [54]. Under optimal conditions (90 min of stirring time, 80 g/L laterite, and pH 3.5), laterite showed the higher removal of humic acids: 97% [55]. The regeneration of the sorbents limits the application of sorption-based therapy once they are spent [19].

Among the membrane separation-based methods, nanofiltration and forward osmosis processes removed around 90% [56] and 98% UVQS [57], respectively, from landfill leachate during water recovery. It was possible to remove 60% HA, 11% FA, and 40% HPI in an ultrafiltration-based membrane bioreactor (MBR) [58]. Humic compounds from landfill leachate had reported removal effectiveness of 43% by coupled lime precipitation (8 g/L lime) and microfiltration, while nanofiltration improved the removal to 86% [59]. However, the pore size of membranes has a significant impact on performance. For example, a study on ultrafiltration of biologically treated leachates showed an increase of UV absorbance removal close to 43% when pore size decreased from 700 nm to 7 nm; in this pore size range, HA and FA were mainly retained; for pore size of 4 nm, additional UV absorbance removal was obtained due to retention of HPI [60, 61]; in consequence, the smaller the pore size, the greater the removal of UVQS. The main handicap of using membranes to remove UVQS is the increase of membrane fouling in the presence of these compounds [62, 63].

3.3 Chemical Treatments

Leachate UVQS can be treated chemically using coagulation-flocculation or advanced chemical oxidation (Fenton, ozone, percarbonate). Chemical treatments have been shown to reduce 7-92% UV absorbance and remove 5-85% UVQS [19].

Coagulation-flocculation with ferric chloride and aluminum sulfate, the two coagulants most typically employed, removed 54%-74% organic matter from landfill leachate; notably, aluminum sulphate only marginally reduced the UV absorbance of treated leachate, but ferric chloride coagulation increased it dramatically by up to 10 times; the UV absorbance increase is probably caused by the complexation of soluble ferric and leachate organic matter [64].

Fenton's oxidation is a very efficient chemical treatment that can remove an average of 84.5% UV absorbance and 67.4% UVQS from leachate [65-67]. However, other chemical treatments, such as ozone treatments, can only remove 5.6-30% of UVQS, although these treatments can reduce UV absorbance by 65% [19, 66, 68]. This is due mainly to O₃ preferential interaction with hydrophobic chemicals, which change to hydrophilic smaller molecular weight fraction after ozone treatment [66]. For instance, following ozone treatment, a 100% decrease in HA, a 16.2% decrease in FA, and a 78% increase in the HPI fraction were obtained [68]. Leachate had also been subjected to sodium percarbonate oxidation, but this treatment is less effective in eliminating UV absorbance (8-43.4%) and UVQS (15.1-15.6%) [69].

Fenton and ozone treatments can be improved by combination with other therapies. Thus, solar photo-Fenton successfully removed 80-85% leachate UVQS [70]. Compared with the O₃-alone process, the removal efficiencies of UVQS was improved in O₃-combined processes (i.e., O₃/H₂O₂ and O₃/UV) approximately by 7-15% [71].

Despite being a powerful and efficient chemical oxidation technique for removing UVQS, the Fenton treatment has disadvantages, such as chemical demand, sludge generation, and foaming during the first pH adjustment [72]. The significant amount of electricity used to generate ozone is the disadvantage of ozone-based treatment [73].

Subcritical water catalytic oxidation [74], supercritical water oxidation [75], and catalyzed wet oxidation [76] also demonstrated efficiency in the treatment of leachate UVQS, showing 66, 61, and 93% of HA removal, respectively. The elevated chemical cost generally restricts the possible use of these treatments [19].

3.4 Electrochemical Treatments

Electrochemical oxidation and electrochemical coagulation are the techniques primarily used in the electrochemical treatments of leachate UVQS. They can remove 57-80% of UVQS and 33.5-89.5% of UV absorbance [19].

Both direct and indirect oxidation can occur during electrochemical oxidation of leachate UVQS; in direct oxidation, a hydroxyl radical ($\cdot\text{OH}$) is produced, which causes oxidation of UVQS on the anode surface; UVQS undergoes indirect oxidation when anodically created oxidants (e.g., $\cdot\text{OH}$, O_3 , $\text{HClO}\dots$) are produced [77].

Electrochemical coagulation involves the production of ions by electricity-mediated electrolysis [78]; ions are then hydrolyzed and polymerized and absorb or aggregate UVQS to be removed as a floated or settled sludge [79]. Due to their better characteristics (accessibility, superior ability to remove contaminants, and continuous production of active ions), aluminum and iron are most frequently used as anodes in the electrochemical coagulation process [80].

Under optimal chemical oxygen demand removal conditions, the electrochemical coagulation process removed fractions of humic substances from the highest to the lowest: 69% HA, 63% FA, and 61% HPI [81]. These variations in removal seem to be due to the different molecular weights and surface loads of the three organic fractions [82]. In the electrochemical oxidation process, the removal of different fractions of humic substances occurred inversely to that of the electrochemical coagulation process, from the lowest to the highest: 40% removed HA, 55% removed FA, and 68% removed HPI [81]. This difference could be explained because in the electrochemical oxidation process, the elimination of UVQS was produced by the action of $\cdot\text{OH}$ radicals, which more easily broke down the less complex molecules from less to more intricate structural complexity: HPI, FA, and HA [83].

Combined electrochemical processes have also been studied for treating landfill leachate UVQS with varied performances. For example, electrochemical methods combined with UV irradiation allowed the removal of 65% of humic compounds from biologically treated landfill leachate after 30 min of treatment [84]. Bioelectrochemical systems (a combination of anaerobic degradation and electrochemical process) achieved a 71-83% UVQS decrease and a 25.5-49.5% UV absorbance decrease after treatment [85, 86]. A membrane electrochemical reactor was developed explicitly for treating UVQS contained in landfill leachate; this process obtained significantly better reductions of both dissolved organic carbon (61.5%) and UV absorbance (63.4%) when compared to a control reactor without a membrane separator; this improved performance was most likely caused by the interactions between humic substances deposition and increased organic oxidation [87]. Electrochemical treatments are associated with important energy consumption [87].

4. Per- and Polyfluoroalkyl Substances (PFAS) Removal

Per- and poly-fluoroalkyl substances (PFAS), according to the Organisation for Economic Co-operation and Development (OECD), are defined as “fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e., with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($-\text{CF}_3$) or a perfluorinated methylene group ($-\text{CF}_2-$) is a PFAS” [88].

PFAS can be divided into two broad categories: perfluoroalkyl acids (PFAA or terminal PFAS) and PFAA-precursors or PFAS precursors; compared with PFAA, PFAA-precursors are usually less stable

and degrade into related PFAA depending upon environmental conditions [89, 90]. PFAS can also be separated into two groups depending on their chain length: long- and short-chained; long-chain PFAS are perfluoroalkyl carboxylic acids (PFCA) with eight or more carbon atoms or perfluoroalkyl sulfonic acids (PFSA) with six or more carbon atoms [91]. Based on the tail ending of the compounds, terminal PFAS include but are not limited to perfluoroalkyl carboxylates (PFCA), perfluoroalkyl sulfonates (PFSA), and perfluorooctane sulfonamide (PFOSA). At the same time, PFCA and PFSA belong to perfluoroalkyl acids (PFAA) [31]. Concentrations of different PFAS groups in landfill leachate are included in Table 2.

Table 2 Concentration range of the most frequently detected species of PFAS in landfill leachate in ng/L [14].

Specie	Concentration range	Specie	Concentration range
PFPeA	0-6500	PFBA	0-3050
PFHPA	0-5900	PFDA	0-1200
PFOS	0-5700	PFHxS	0-1150
PFOA	0-5000	PFNA	0-750

Since PFAS are discharged from wastes containing PFAS, landfills represent the last stage in the life cycle of PFAS [89]. Consequently, PFAS were detected in the landfill leachate, being the most frequently seen species of perfluorbutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluoroheptanoic acid (PFHPA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA) perfluorodecanoic acid (PFDA), perfluorohexane sulfonate (PFHxS), perfluorooctane sulfonate (PFOS) [14, 92, 93].

4.1 Biological Treatments

Leachate landfills containing PFAS can be treated using biological treatments [33, 94, 95]. When the conventional activated sludge process in wastewater treatment plants was used for landfill leachate [31], it failed in PFAS degradation [96]. Some bio-leachate treatment matrices, such as aerobic landfill reactors and membrane bioreactors, have even been found to have an overall increasing tendency in PFAS chemicals [33, 94, 95]. This increase could be explained by the persistence of perfluoroalkyl acids against biodegradation [97] and the possible biodegradation of fluorinated precursor compounds to perfluoroalkyl acids during biological processes, which was reported for biological treatment in wastewater treatment plants [98, 99].

However, a 61% decrease in the concentrations of PFAS after membrane bioreactor treatment has also been reported [94]; it was attributed to the loss of PFAS due to water-to-air transfer by bursting bubbles in the aeration tanks and the sorption of PFAS on the activated sludge as the concentrations of these PFAS in the sludge phase increased.

These different results could be due to the main factors that influence the biological degradation of PFAS:

- Microbial species and quantity: Different microorganisms have different degradation efficiencies and adaptabilities to PFAS. For instance, the PFAS contaminants can be degraded by ligninolytic fungi [100] or via biodegradation by aerobic bacteria [97] into non-toxic compounds such as carbon dioxide, water, and ammonia.

- Temperature and pH: Microbial activity and PFAS breakdown efficiency can be increased at the appropriate temperature and pH [94]. According to this, it is vital to choose the best environmental conditions based on the circumstances because different microorganisms have varied requirements.
- PFAS structure and concentration: The capacity of microorganisms to degrade PFAS can be influenced by its structure and concentration. Thus, long-chain PFAS are more challenging to break down than short-chain PFAS [101], and microorganisms may experience physiological changes and/or inhibitory effects because of PFAS exposure [102-104].
- Other environmental factors: Degradation of PFAS can be impacted by nutrients, organic matter, and oxygen. For example, PFOS and related PFAS mineralization should involve sequential aerobic and anaerobic degradation [105].

According to these factors, the biological treatment of PFAS has some disadvantages: it is a relatively slow process that needs time and conditions, and it can produce intermediates that require additional treatment to avoid secondary pollution [33, 90, 94, 95].

A promising approach to achieving appropriate leachate effluent values is the combination of physical, chemical, and biological treatments, for example, a biological treatment combined with reverse osmosis, activated carbon, or nanofiltration [31].

4.2 Physical Treatments

Most physical treatments rely on sorption and membrane separation-based techniques and remove between 61 and 100% of PFAS present in leachate [102, 106].

The sorption-based techniques include preferentially carbon as an adsorbent. Activated carbon can efficiently remove PFAA from leachate (70%-99% removal) [107]. Granular activated carbon effectively removed PFAS from leachate [108] but powdered activated carbon and activated carbon fiber showed better adsorption performance than granular activated carbon due to their highest surface area [109]. Biochar produced from biomass pyrolysis at 500-600°C can adsorb 80% of long-chain PFAS and is highly stable [110]; if biochar is created using a pyrolytic combustion integrated process, it may adsorb 90%, while short-chain PFAS performs poorly [111]. The adsorption of short-chain PFAS can be improved by using a modified coal fly ash as an adsorbent [112]. Coal-based magnetic activated carbon removed 72.8-89.6% PFCA with 8 g/150 mL adsorption dosage and 120 min contact time [113]. However, carbon sorption-based techniques have disadvantages, such as the tendency to become saturated and require regular replacement or regeneration [107].

Wetlands have also been used to remove PFAS from landfill leachate. Studies have shown that several plants can adsorb PFAS, and selecting suitable plant species can improve the adsorption effect [114]. Overall, the constructed wetland treatment system removed 61% of total PFAS and 50-96% of individual PFAS [106]. The removal of PFAS from landfill leachates in constructed wetlands can be enhanced using young plants or species with a high affinity for PFAS and substrates with high PFAS sorption capacity [115]. Despite being a green and sustainable method of PFAS remediation, phytoremediation has many drawbacks and restrictions, including a high time consumption, harmful effects on plants, and risk of entering PFAS into food chains, that restrict the use of wetlands in PFAS removal [116].

Studies carried out have proven that membrane-based treatment technology is successful in removing PFAS from leachate. Ultrafiltration and nanofiltration membranes have been utilized to

remove PFAS from leachate, exhibiting a success of more than 90% [95]. Systems fitted with reverse osmosis showed significant reductions (98-99%) of PFAS in the permeate [117]. An explanation for the different efficiency of these treatment systems in removing PFCA from the leachate is possibly in the characteristics of the membranes. Ultrafiltration, nanofiltration, and reverse osmosis are treatments working with semipermeable membranes, which separate the leachate into a clean permeate and a contaminated residue. The membrane pores of reverse osmosis are smaller than in ultrafiltration and nanofiltration and are, therefore, more effective for PFC removal than ultrafiltration and nanofiltration [118]. Although membrane filtration systems present significant advantages in PFAS removal (including low energy consumption, continuous separation, and enhanced treatment effectiveness), some issues can complicate the use of membranes, such as high levels of organic compounds, heavy metals, suspended solids, and salinity in leachate which can cause fouling of the membrane [119, 120], and concentrate management [121].

As opposed to membrane technology, membrane distillation uses hydrophobic membranes to keep non-volatile solutes out of the membrane pores [122, 123]. Because the regulated PFAS in the leachate are not volatile, theoretically, membrane distillation could eliminate them from the leachate with a rejection close to 100% [102]. Effectively, hybrid microporous materials with incorporated metal-organic framework showed a 98.4% rejection rate for total PFAS. However, it should be noted that the maximum rejection to PFOA was 65.6%, much lower than its rejection to total PFAS [100]. Despite its high PFAS rejection rate, membrane distillation has disadvantages such as energy-intensive water vaporization, low permeate flux, and membrane fouling issues [63, 107].

Foam fractionation is another technology that has been tested for leachate treatment. The efficiency of the foaming separation for concentrating PFAS changed by a compound with an average removal percentage (the percent difference between PFAS in leachate before and after foam removal) of 69% [124]; it was demonstrated that foam fractionation was successful in removing $\geq 98.7\%$ PFOS, $\geq 99.7\%$ PFOA, and $\geq 98.8\%$ PFHxS from the feed stream without using absorbent media or chemical amendment consumables [125]. It was verified that long-chain PFAS were more effectively removed through foaming ($>90\%$ on average) than short-chain PFAS, which had relatively low percent removal values ($<30\%$ on average) [126]. Foaming can be utilized most efficiently in systems with high concentrations of long chains of PFAS [127]. Treatment efficiency decreased with decreasing contact time, air flow rate, and collected foam fraction [126]. The most significant advantage of the foam fractionation technology is its simplicity [126] and easy application at a relatively low cost at most landfills, where leachate aeration is now customary practice [124]. The main disadvantage is that PFAS released into the air instead of captured in the foam may still end up in the environment through long-range transport [128].

4.3 Chemical Treatments

PFAS in leachate can be effectively removed by chemical treatments using advanced chemical oxidation (photocatalytic oxidation or plasma technology). These treatments have removed 84-99.9% of PFAS [43].

Heterogeneous photocatalytic oxidation with semiconductor-based catalysts effectively degrades PFAS in landfill leachate under ultraviolet irradiation [129, 130]. A 3DP photocatalyst fabricated using polylactic acid compounded with TiO_2 (15 wt%) and 3D printed into tiles effectively decreased concentrations of PFAS in landfill leachate; photocatalytic degradation was achieved for

most of the PFAS evaluated: PFOS, PFOA, PFHPA, PFHxS, PFNA, PFDA, and PFOSAm; greater than 80% removal of PFOS, PFNA, PFDA, and PFOSAm was achieved with 24-h of photocatalysis [129]. An adsorptive photocatalyst of iron-doped, carbon-modified composite (Fe/TNTs@AC) was also able to remove PFAS selectively; at a dosage of 10 g/L, fresh Fe/TNTs@AC removed >95% of 13 PFAS from the leachate within 2 h, 86% after first regeneration, and 74% when reused three times; Fe/TNTs@AC degraded >92% of 18 PFAS in 8 h under the field conditions, and when the PFAS-laden solids were subjected to the UV-H₂O₂ system, approximately 84% of 16 PFAS in the solid phase were degraded; nevertheless, Fe/TNTs@AC was less efficient for PFBA and PFPeA owing to the transformation of longer-chain homologs into these short-chain PFAS and competition of adsorption sites by the longer-chain PFAS [130]. Extremely low or high pH values may alter photocatalysts' stability and catalytic activity [107].

Non-thermal plasma technology was evaluated for PFAS destruction in landfill leachate. Plasma discharge in an Ar atmosphere destroyed PFAS compounds present in six leachate samples; the highest removal efficiency was achieved for long-chain PFAA (>99.9% in 40 min) followed by PFAS precursors (99.9% in 60 min) and short-chain PFAA (10-99.9% after 120 min of plasma treatment [43]; process efficiency was not affected by the presence of high concentrations of organic matter but was enhanced by addition of cationic surfactants [43]. Slower removal of short-chain PFAS compared to long-chain compounds can be attributed to differences in surface activity and their production as byproducts from longer-chain compound destruction [131]. Some aspects of contaminated water, such as pH and organic matter or nitrate concentrations, can directly lower the effectiveness of non-thermal plasma treatment [132]. One of the main concerns associated with plasma is its high energy consumption in some cases. However, producing non-thermal plasma with an efficient reactor type and power supply sources can substantially reduce the energy requirements [133].

Fenton's oxidation, sonochemistry, sub-critical and supercritical water oxidation, microwave-hydrothermal treatment, and wet air oxidation have proved to degrade more than 90% of the PFAS (especially long-chain PFAS like PFOA and PFOS) in water [31, 115, 134]. Still, the degradation of PFAS in landfill leachates have not been evidenced.

4.4 Electrochemical Oxidation

Electrochemical oxidation can efficiently eliminate PFAS (up to 99.7%) via the combined effects of direct and indirect oxidation [135].

In electrochemical treatment of landfill leachates with boron-doped diamond electrodes, PFAS removal efficiency was high (99.7%) [107]; PFOA and PFOS removal were dependent on current density: at higher current density (75 mA/cm²) it was possible to obtain an average removal efficiency of 80% for PFOA and 78% for PFOS; at lower current density (25 mA/cm²), the efficiencies were reduced to half [136]; this is due to the competing reactions within a complex matrix [136]. In electrochemical treatment with Pd/Sn-doped electrodes (Pd (1%)-SnO₂), long-chain PFAS in raw leachate were removed at an energy consumption of 20 Wh/L, but more than 100 Wh/L energy input was needed to remove about 80% of short-chain PFAS [43]; the required treatment time was inversely correlated with the chain lengths: PFOS and PFOA were rapidly removed at an energy input <20 Wh/L and a retention time of 18 min but the increase in short-chain PFAS (such as PFBA and PFBS) concentrations was prominent, probably due to the breakdown of PFAS precursors [43]; the

short-chain PFAS were further degraded by increasing the treatment duration [43]; a significant elimination of formed PFBA was achieved when energy input surpassed 400 Wh/L [43]. In electrochemical oxidation, the possible formation of toxic byproducts, such as HF, during treatment could be a problem [134]. Scaling up this technology is the major challenge for the full-scale use of electrochemical oxidation in PFAS treatment due to the low PFAS concentrations, high energy consumption, and costly acquisition of electrodes [137, 138]. Incorporating electrochemical oxidation after plasma treatment could be an effective strategy to remove short-chain PFAS without surfactant addition, although plasma alone with surfactant addition would be more energy effective [43].

5. Efficacy Comparison of the Optimal Treatments for UVQS and PFAS Removal

Figure 1 compares the removal efficiency of UVQS by the different treatments analyzed. According to the figure, the maximum removal efficacy sequence is:

Physical treatments > Chemical treatments > Electrochemical treatments > Biological treatments

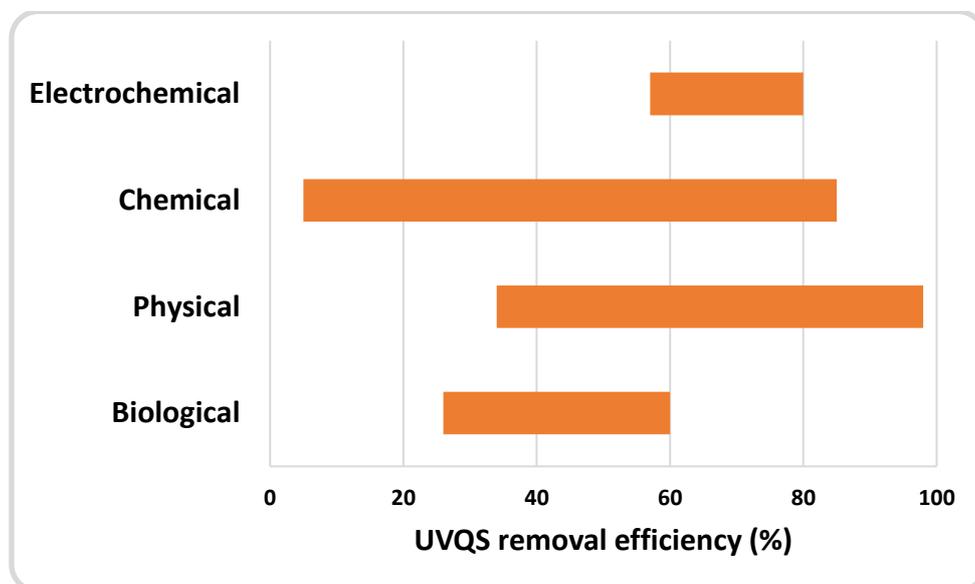


Figure 1 UVQS removal efficiency (%) of the treatments.

In the best case, the biological treatments only removed 60% of the UVQS in landfill leachate [19]. However, electrochemical treatments worked efficiently when combined with biological treatments (anaerobic degradation + electrochemical process), achieving, on average, 80% UVQS removal [83, 84]. High removal efficiencies (85%) were obtained with chemical treatments like solar photo-Fenton system [70].

Physical treatments such as adsorption on powered active carbon [54] or laterite [55] resulted in the most efficient processes based on sorption with 95% and 97% UVQS removal, respectively. In comparison, osmosis was the most efficient membrane separation-based method, with 98% of UVQS elimination [56].

As shown in Figure 2, biological treatments are the least efficient option for PFAS removal. Significant variations in the elimination effectiveness of this treatment can be seen. For example, positive PFAS removal efficiency values were obtained in up-flow anaerobic sludge blankets (UASBs)

and denitrification units, whereas negative results were found in nitrification units [42]. The obtention of negative removal results, corresponding to the formation of PFAS in some biological systems, has been explained in section 4.1 [97, 99].

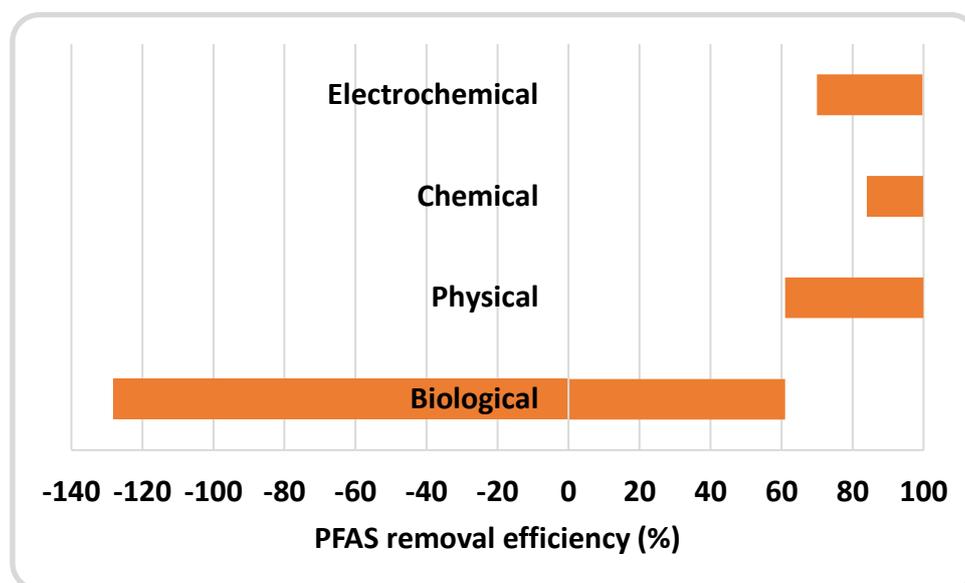


Figure 2 PFAS removal efficiency (%) of the different treatments.

Similar maximum efficiency, nearly 100% (Figure 2), was observed for some physical, chemical, and electrochemical treatments:

- The adsorption on powdered active carbon [107], the reverse osmosis [117], and the membrane distillation [102] stand out as the best physical treatments for PFAS removal.
- The non-thermal plasma method was the most effective process among the chemical treatments [43].
- The boron-doped diamond electrodes contributed to the electrochemical treatment's highest PFAS degradation efficiency [107].

According to what has been discussed previously, two physical treatments (adsorption on powdered activated carbon and osmosis) can remove both UVQS and PFAS. This coincidence suggests that future landfill leachate studies should explore these treatment techniques to remove PFAS and UVQS simultaneously. As said in the Introduction Section, there are no studies on the simultaneous removal of PFAS and UVQS from landfill leachate; however, some research on adsorption or membrane-based processes has proved that these techniques are very efficient for the simultaneous removal of very different types of pollutants from wastewaters [139-144]. These observations justify the suggestion for future studies on the simultaneous removal of PFAS and UVQS from landfill leachate.

6. Conclusions

This review gives up-to-date information on recent findings in the UVQS and PFAS degradation field through physical, chemical, electrochemical, and biological treatments. Results from this current review showed that:

- Conventional biological treatments, like the activated sludge process, cannot remove UVQS or PFAS from the landfill leachate. Combinations of biological and physicochemical therapies, such as membrane bioreactors, can improve the efficiency of the process.
- Physical treatments show better effectiveness for emerging pollutants. Sorption-based processes result in an exciting option for removal, although the regeneration of sorbents limits their application once they are spent. Membrane-based processes have been revealed as a promising technology to remove UVQS and PFAS, having their performance controlled by the membrane's pore size and limited by the membrane fouling and concentrate management. Membrane distillation and foam fractionation are also remarkable options to eliminate PFAS restricted by membrane fouling and/or energy consumption.
- Chemical treatments, such as advanced oxidation-based processes, have also been capable of eliminating both UVQS and PFAS. The primary concerns associated with these procedures are often the high cost and complexity of operation that can restrict the potential use of these treatments.
- Electrochemical treatments, like electrochemical oxidation, can successfully remove UVQS and PFAS. The high energy consumption restricts the application of electrochemical processes. Combining electrochemical treatments with physical therapies, such as membranes, or chemical treatments, such as plasma processes, can improve the removal of UVQS or PFAS.

The overall evaluation of the treatments shows that technologies like adsorption or osmosis can efficiently remove PFAS and UVQS from landfill leachate. This conclusion suggests that both pollutants could be released simultaneously with a single treatment based on one of these simple, green, and efficient technologies. The simultaneous method would require lower costs and space compared to traditional methods that combine two or more techniques. In addition, the concurrent process could perhaps show synergistic removal performance. Therefore, future research in landfill leachate should be focused on the simultaneous removal of the UVQS and PFAS by one of these treatment methods, emphasizing the synergistic and economic effects of the process.

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

References

1. The World Bank. Solid waste management [Internet]. Washington, DC: The World Bank; 2023 [cited date 2023 November 20]. Available from: <https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management>.
2. Chu EW, Karr JR. Environmental impact: Concept, consequences, measurement. In: Reference module in the life sciences. Amsterdam: Elsevier; 2017.
3. Bidzakin JK, Graves A, Awunyo-Vitor D, Yeboah O, Yahaya I, Wahaga E. Utilization of organic fertilizer in Ghana: Implications for crop performance and commercialization. *Adv Agric*. 2023; 2023: 8540278.

4. Show PL, Pal P, Leong HY, Juan JC, Ling TC. A review on the advanced leachate treatment technologies and their performance comparison: An opportunity to keep the environment safe. *Environ Monit Assess.* 2019; 191: 227.
5. Luo H, Cheng Y, He D, Yang EH. Review of leaching behavior of municipal solid waste incineration (MSWI) ash. *Sci Total Environ.* 2019; 668: 90-103.
6. Mojiri A, Ziyang L, Hui W, Ahmad Z, Tajuddin RM, Abu Amr SS, et al. Concentrated landfill leachate treatment with a combined system including electro-ozonation and composite adsorbent augmented sequencing batch reactor process. *Process Saf Environ Prot.* 2017; 111: 253-262.
7. Nath A, Debnath A. A short review on landfill leachate treatment technologies. *Mater Today Proc.* 2022; 67: 1290-1297.
8. Baderna D, Caloni F, Benfenati E. Investigating landfill leachate toxicity in vitro: A review of cell models and endpoints. *Environ Int.* 2019; 122: 21-30.
9. Teng C, Zhou K, Peng C, Chen W. Characterization and treatment of landfill leachate: A review. *Water Res.* 2021; 203: 117525.
10. Mojiri A, Aziz HA, Zaman NQ, Aziz SQ, Zahed MA. Metals removal from municipal landfill leachate and wastewater using adsorbents combined with biological method. *Desalin Water Treat.* 2016; 57: 2819-2833.
11. Salam M, Nilza N. Hazardous components of landfill leachates and its Remediation. In: *Soil contamination*. London, UK: IntechOpen; 2021. pp. 167-176.
12. Deng M, Kuo DT, Wu Q, Zhang Y, Liu X, Liu S, et al. Organophosphorus flame retardants and heavy metals in municipal landfill leachate treatment system in Guangzhou, China. *Environ Pollut.* 2018; 236: 137-145.
13. Propp VR, De Silva AO, Spencer C, Brown SJ, Catingan SD, Smith JE, et al. Organic contaminants of emerging concern in leachate of historic municipal landfills. *Environ Pollut.* 2021; 276: 116474.
14. Golwala H, Saha B, Zhang X, Bolyard SC, He Z, Novak JT, et al. Advancement and challenges in municipal landfill leachate treatment—The path forward! *ACS ES T Water.* 2022; 2: 1289-1300.
15. Iravanian A, Ravari SO. Types of contamination in landfills and effects on the environment: A review study. *IOP Conf Ser Earth Environ Sci.* 2020; 614: 012083.
16. Ozbay G, Jones M, Gadde M, Isah S, Attarwala T. Design and operation of effective landfills with minimal effects on the environment and human health. *J Environ Public Health.* 2021; 2021: 6921607.
17. Dereli RK, Clifford E, Casey E. Co-treatment of leachate in municipal wastewater treatment plants: Critical issues and emerging technologies. *Crit Rev Environ Sci Technol.* 2021; 51: 1079-1128.
18. Qiu J, Lü F, Zhang H, He PJ. Emerging contaminants: Are they a big concern for leachate cotreatment in municipal wastewater treatment plants? *ACS ES T Water.* 2023; 3: 3-5.
19. Iskander SM, Zhao R, Pathak A, Gupta A, Pruden A, Novak JT, et al. A review of landfill leachate induced ultraviolet quenching substances: Sources, characteristics, and treatment. *Water Res.* 2018; 145: 297-311.
20. GodvinSharmila V, Shanmugavel SP, Tyagi VK, Banu JR. Microplastics as emergent contaminants in landfill leachate: Source, potential impact and remediation technologies. *J Environ Manag.* 2023; 343: 118240.

21. Wang K, Reguyal F, Zhuang T. Risk assessment and investigation of landfill leachate as a source of emerging organic contaminants to the surrounding environment: A case study of the largest landfill in Jinan City, China. *Environ Sci Pollut Res.* 2021; 28: 18368-18381.
22. Liu L, Shi L, Li P, Ma X, Hou X, Jiang S, et al. Seasonal dynamics survey and association analysis of microbiota communities, antibiotic resistance genes distribution, and biotoxicities characterization in landfill-leachate. *Ecotoxicol Environ Saf.* 2022; 245: 114103.
23. Feng D. Environmental, human health, and economic implications of landfill leachate treatment for PFAS removal. Durham, NH: University of New Hampshire; 2020.
24. Bolyard BC, Motlagh AM, Lozinski D, Reinhart DR. Impact of organic matter from leachate discharged to wastewater treatment plants on effluent quality and UV disinfection. *Waste Manage.* 2019; 88: 257-267.
25. Ehrig HJ, Stegmann R. Leachate quality. In: *Solid waste landfilling. Concepts, processes, technologies.* Amsterdam: Elsevier; 2019. pp. 511-539.
26. Ma S, Zhou C, Pan J, Yang G, Sun C, Liu Y, et al. Leachate from municipal solid waste landfills in a global perspective: Characteristics, influential factors and environmental risks. *J Clean Prod.* 2022; 333: 130234.
27. Al Raisi SA. The generation, composition and fate of landfill leachate: A review. *J Environ Sci.* 2022; 3: 105-109.
28. Gómez M, Corona F, Hidalgo MD. Variations in the properties of leachate according to landfill age. *Desalin Water Treat.* 2019; 159: 24-31.
29. Hamid H, Li LY, Grace JR. Review of the fate and transformation of per and polyfluoroalkyl substances (PFASs) in landfills. *Environ Pollut.* 2018; 235: 74-84.
30. Kotthoff M, Müller J, Jürling H, Schlummer M, Fiedler D. Perfluoroalkyl and polyfluoroalkyl substances in consumer products. *Environ Sci Pollut Res.* 2015; 19: 14546-14559.
31. Wei Z, Xu T, Zhao D. Treatment of per- and polyfluoroalkyl substances in landfill leachate: Status, chemistry and prospects. *Environ Sci Water Res Technol.* 2019; 5: 1814-1835.
32. Li K, Gao P, Xiang P, Zhang X, Cui X, Ma LQ. Molecular mechanisms of PFOA-induced toxicity in animals and humans: Implications for health risks. *Environ Int.* 2017; 99: 43-54.
33. Solo-Gabriele HM, Jones AS, Lindstrom AB, Lang JR. Waste type, incineration, and aeration are associated with per- and polyfluoroalkyl levels in landfill leachates. *Waste Manage.* 2020; 107: 191-200.
34. Li R, Li L, Zhang Z, Chen G, Tang Y. Limiting factors of heavy metals removal during anaerobic biological pretreatment of municipal solid waste landfill leachate. *J Hazard Mater.* 2021; 416: 126081.
35. Iskander S. *Advanced technologies for resource recovery and contaminants removal from landfill leachate.* Blacksburg, VA: Virginia Polytechnic Institute and State University; 2019.
36. Kliaugaitė D, Yasadi K, Euerink G, Bijmans MF, Racys V. Electrochemical removal and recovery of humic-like substances from wastewater. *Sep Purif Technol.* 2013; 108: 37-44.
37. Alomar T, Qiblawey H, Almomani F, Al-Raoush RI, Han DS, Ahmad NM. Recent advances on humic acid removal from wastewater using adsorption process. *J Water Process Eng.* 2023; 53: 103679.
38. Łomińska D, Anielak AM. The content of fulvic acids in the primary effluent at the Płaszów WWTO in Kraków. *Proceedings of the 9th Conference on Interdisciplinary Problems in*

- Environmental Protection and Engineering EKO-DOK; 2017 April 20-23; Boguszow-Gorce, Poland. Paris: EDP Sciences.
39. Puangmalai N. Characterization of dissolved organic matter in treated textile wastewater from membrane bioreactor. Bangkok: Chulalongkorn University; 2019.
 40. Bai X, Son Y. Perfluoroalkyl substances (PFAS) in surface water and sediments from two urban watersheds in Nevada, USA. *Sci Total Environ.* 2021; 751: 141622.
 41. Thompson KA, Mortazavian S, Gonzalez DJ, Bott C, Hooper J, Schaefer CE, et al. Poly- and Perfluoroalkyl substances in municipal wastewater treatment plants in the United States: Seasonal patterns and meta-analysis of long-term trends and average concentrations. *ACS ES T Water.* 2022; 2: 690-700.
 42. Liu X, Huang X, Wei X, Zhi Y, Qian S, Li W, et al. Occurrence and removal of per- and polyfluoroalkyl substances (PFAS) in leachates from incineration plants: A full-scale study. *Chemosphere.* 2023; 313: 137456.
 43. Loganathan S, Yang S, Yang Y, Thagard SM, Grieco S, Holsen TM. Innovative technologies to treat per- and polyfluoroalkyl substances (PFAS) in landfill leachate. Final report. New York: Environmental Research and Education Foundation; 2023.
 44. Carter CH, Leang AL, Delistraty DA. Per- and polyfluoroalkyl substances (PFAS) in landfill leachate: Selected landfills in Washington State. Solid waste management program. Olympia, WA: Washington State Department of Ecology; 2022; 22-07-011.
 45. Keane D, Crawford S, Moyer E, Ball R, Taylor F. Per- and polyfluoroalkyl substances (PFAS) remediation workshop. Proceedings of the 35th Annual Int. Conference on Soils, Sediments, Water and Energy; 2019 October 22; Amherst, MA, USA. Boston, MA: XDD, LLC.
 46. Lu G, Shao P, Zheng Y, Yang Y, Gai N. Perfluoroalkyl substances (PFASs) in rivers and drinking waters from Qingdao, China. *Int J Environ Res Public Health.* 2022; 19: 5722.
 47. Liu Z, Liu P. Research progress on degradation of ultraviolet quenching substances in landfill leachate. *Ind Water Treat.* 2021; 41: 1-10.
 48. Guvenc SY, Dincer K, Varank G. Performance of electrocoagulation and electro-Fenton processes for treatment of nanofiltration concentrate of biologically stabilized landfill leachate. *J Water Proc Eng.* 2019; 31: 10086.
 49. Abdel-Shafy HI, Ibrahim AM, Al-Sulaiman AM, Okasha RA. Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. *Ain Shams Eng J.* 2024; 15: 102293.
 50. Pathak A, Pruden A, Novak JT. Two-stage Anaerobic Membrane Bioreactor (AnMBR) system to reduce UV absorbance in landfill leachates. *Bioresour Technol.* 2018; 251: 135-142.
 51. Zhao R, Gupta A, Novak JT, Goldsmith CD, Driskill N. Characterization and treatment of organic constituents in landfill leachates that influence the UV disinfection in the publicly owned treatment works (POTWs). *J Hazard Mater.* 2013; 258: 1-9.
 52. Ateia M, Apul OG, Shimizu Y, Muflihah A, Yoshimura C, Karanfil T. Elucidating adsorptive fractions of natural organic matter on carbon nanotubes. *Environ Sci Technol.* 2017; 51: 7101-7110.
 53. Iskander SM, Novak JT, Brazil B, He Z. Simultaneous energy generation and UV quencher removal from landfill leachate using a microbial fuel cell. *Environ Sci Pollut Res.* 2017; 24: 26040-26048.

54. Deng Y, Jung C, Zhao R, Torrens K, Wu L. Adsorption of UV-quenching substances (UVQS) from landfill leachate with activated carbon. *Chem Eng J*. 2018; 350: 739-746.
55. Coulibaly Y, Kone T, Ouattara PJM, Coulibaly SL, Mbey JA. Attenuation of the proportion of humic acid in the landfill leachate by laterite. *J Mater Environ Sci*. 2021; 12: 1561-1580.
56. Iskander SM, Zou S, Brazil B, Novak JT, He Z. Energy consumption by forward osmosis treatment of landfill leachate for water recovery. *Waste Manage*. 2017; 63: 284-291.
57. de Almeida R, de Souza Couto JM, Gouvea RM, de Almeida Oroski F, Bila DM, Quintaes BR, et al. Nanofiltration applied to the landfill leachate treatment and preliminary cost estimation. *Waste Manag Res*. 2020; 38: 1119-1128.
58. Zolfaghari M, Drogui P, Brar SK, Buelna G, Dube R. Unwanted metals and hydrophobic contaminants in bioreactor effluents are associated with the presence of humic substances. *Environ Chem Lett*. 2017; 15: 489-494.
59. Amaral MC, Pereira HV, Nani E, Lange LC. Treatment of landfill leachate by hybrid precipitation/microfiltration/nanofiltration process. *Water Sci Technol*. 2015; 72: 269-276.
60. Gupta A, Zhao RZ, Novak JT, Goldsmith CD. Variation in organic matter characteristics of landfill leachates in different stabilisation stages. *Waste Manag Res*. 2014; 32: 1192-1199.
61. Zhao R, Gupta A, Novak JT, Goldsmith CD, Driskill N. Characterization and treatment of organic constituents in landfill leachates that influence the UV disinfection in the publicly owned treatment works (POTWs). *J Hazard Mater*. 2013; 258: 1-9.
62. Amaral MC, Moravia WG, Lange LC, Roberto MM, Magalhaes NC, dos Santos TL. Nanofiltration as post-treatment of MBR treating landfill leachate. *Desalin Water Treat*. 2015; 53: 1482-1491.
63. Gripa E, Daflon SD, de Almeida R, da Fonseca FV, Campos JC. Landfill leachate treatment by high-pressure membranes and advanced oxidation techniques with a focus on ecotoxicity and by-products management: A review. *Process Saf Environ Prot*. 2023; 173: 747-764.
64. Patel HV, Brazil B, Lou HH, Jha MK, Luster-Teasley S, Zhao R. Evaluation of the effects of chemically enhanced primary treatment on landfill leachate and sewage co-treatment in publicly owned treatment Works. *J Water Proc Eng*. 2021; 42: 102116.
65. Gupta A, Zhao RZ, Novak JT, Goldsmith CD. Application of Fenton's reagent as a polishing step for removal of UV quenching organic constituents in biologically treated landfill leachates. *Chemosphere*. 2014; 105: 82-86.
66. Jung C, Deng Y, Zhao R, Torrens K. Chemical oxidation for mitigation of UV-quenching substances (UVQS) from municipal landfill leachate: Fenton process versus ozonation. *Water Res*. 2017; 108: 260-270.
67. Moravia WG, Amaral MC, Lange LC. Evaluation of landfill leachate treatment by advanced oxidative process by Fenton's reagent combined with membrane separation system. *Waste Manage*. 2013; 33: 89-101.
68. Wang HW, Wang YN, Li XY, Sun YJ, Wu H, Chen DL. Removal of humic substances from reverse osmosis (RO) and nanofiltration (NF) concentrated leachate using continuously ozone generation-reaction treatment equipment. *Waste Manage*. 2016; 56: 271-279.
69. Iskander SM, Novak JT, Brazil B, He Z. Percarbonate oxidation of landfill leachates towards removal of ultraviolet quenchers. *Environ Sci Wat Res*. 2017; 3: 1162-1170.
70. Silva T, Silva ME, Cunha-Queda AC, Fonseca A, Saraiva I, Sousa MA, et al. Multistage treatment system for raw leachate from sanitary landfill combining biological nitrification denitrification/solar photo-Fenton/biological processes, at a scale close to industrial

- Biodegradability enhancement and evolution profile of trace pollutants. *Water Res.* 2013; 47: 6167-6186.
71. Wang HW, Li XY, Hao ZP, Sun YJ, Wang YN, Li WH, et al. Transformation of dissolved organic matter in concentrated leachate from nanofiltration during ozone-based oxidation processes (O_3 , O_3/H_2O_2 and O_3/UV). *J Environ Manage.* 2017; 191: 244-251.
 72. Kastanek F, Spacilova M, Krystynik P, Dlaskova M, Solcova O. Fenton reaction—Unique but still mysterious. *Processes.* 2023; 11: 432.
 73. Crutchik D, Franchi O, Jeison D, Vidal G, Pinto A, Pedrouso A, et al. Techno-economic evaluation of ozone application to reduce sludge production in small urban WWTPs. *Sustainability.* 2022; 14: 2480.
 74. Zhai YB, Zhu L, Zhu Y, Peng C, Wang TF, Liu XM, et al. Simultaneous total organic carbon and humic acid removals for landfill leachate using subcritical water catalytic oxidation based on response surface methodology. *Water Air Soil Pollut.* 2016; 227: 273.
 75. Martins DC, Scandelai AP, Cardozo-Filho L, Tavares CR. Supercritical water oxidation treatment of humic acid as a model organic compound of landfill leachate. *Can J Chem Eng.* 2020; 98: 868-878.
 76. Song C, Lv Y, Qin X, Guo C, Cui J, Kaghembega WS. Optimization of catalytic wet oxidating fulvic acid with zero-valent copper chitosan activated carbon ball as the catalyst. *Sci Rep.* 2021; 11: 13998.
 77. Liu J, Ren N, Qu C, Lu S, Xiang Y, Liang D. Recent advances in the reactor design for industrial wastewater treatment by electro-oxidation process. *Water.* 2022; 14: 3711.
 78. Hamid MA, Aziz HA, Yusoff MS. Electrocoagulation process in the treatment of landfill leachate. In: *Sustainable solutions for environmental pollution*. 1st ed. Beverly, MA: Scrivener Publishing Wiley; 2021. pp. 257-283.
 79. Song PP, Yang ZH, Zeng GM, Yang X, Xu HY, Wang LK, et al. Electrocoagulation treatment of arsenic in wastewaters: A comprehensive review. *Chem Eng J.* 2017; 317: 707-725.
 80. Magnisali E, Yan Q, Vayenas DV. Electrocoagulation as a revived wastewater treatment method—practical approaches: A review. *J Chem Technol Biotechnol.* 2022; 97: 9-25.
 81. Martínez-Cruz A, Rojas-Valencia MN. Evaluation of the different fractions of organic matter in an electrochemical treatment system applied to stabilized leachates from the Bordo Poniente landfill in Mexico City. *Appl Sci.* 2023; 13: 5605.
 82. Dia O, Drogui P, Buelna G, Dubé R, Ihsen BS. Electrocoagulation of bio-filtrated landfill leachate: Fractionation of organic matter and influence of anode materials. *Chemosphere.* 2017; 168: 1136-1141.
 83. Fernandes A, Pacheco MJ, Ciríaco L, Lopes A. Review on the electrochemical processes for the treatment of sanitary landfill leachates: Present and future. *Appl Catal B.* 2015; 176: 183-200.
 84. Xiao SH, Peng JF, Song YH, Zhang DS, Liu RX, Zeng P. Degradation of biologically treated landfill leachate by using electrochemical process combined with UV irradiation. *Sep Purif Technol.* 2013; 117: 24-29.
 85. Iskander SM, Novak JT, Brazil B, He Z. Simultaneous energy generation and UV quencher removal from landfill leachate using a microbial fuel cell. *Environ Sci Pollut Res.* 2017; 24: 26040-26048.
 86. Zhang GD, Jiao Y, Lee DJ. Transformation of dissolved organic matters in landfill leachate—bioelectrochemical system. *Bioresour Technol.* 2015; 191: 350-354.

87. Liu X, Novak JT, He Z. Removal of landfill leachate ultraviolet quenching substances by electricity induced humic acid precipitation and electrooxidation in a membrane electrochemical reactor. *Sci Total Environ.* 2019; 689: 571-579.
88. OECD. Reconciling terminology of the universe of per- and polyfluoroalkyl substances: Recommendations and practical guidance. Paris: OECD Series on Risk Management; 2021; No. 61.
89. Lang JR, Allred BM, Field JA, Levis JW, Barlaz MA. National estimate of per-and polyfluoroalkyl substance (PFAS) release to US municipal landfill leachate. *Environ Sci Technol.* 2017; 51: 2197-2205.
90. Wang B, Yao Y, Chen H, Chang S, Tian Y, Sun H. Per- and polyfluoroalkyl substances and the contribution of unknown precursors and short-chain (C2–C3) perfluoroalkyl carboxylic acids at solid waste disposal facilities. *Sci Total Environ.* 2020; 705: 135832.
91. Minnesota Pollution Control Agency. Evaluation of current alternatives and estimated cost curves for pfas removal and destruction from municipal wastewater, biosolids, landfill leachate, and compost contact water. Final report. Baxter, MN: Minnesota Pollution Control Agency; 2023; 952.832.2600.
92. Rahman MF, Peldszus S, Anderson WB. Behaviour and fate of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in drinking water treatment: A review. *Water Res.* 2014; 50: 318-340.
93. Zhang M, Zhao X, Zhao D, Soong TY, Tian S. Poly- and perfluoroalkyl substances (PFAS) in landfills: Occurrence, transformation and treatment. *Waste Manage.* 2023; 155: 162-178.
94. Yan Y, Cousins IT, Zhang C, Qi Z. Perfluoroalkyl acids in municipal landfill leachates from China: Occurrence, fate during leachate treatment and potential impact on groundwater. *Sci Total Environ.* 2015; 524: 23-31.
95. Fuertes I, Gómez-Lavín S, Elizalde MP, Urtiaga A. Perfluorinated alkyl substances (PFASs) in northern Spain municipal solid waste landfill leachates. *Chemosphere.* 2017; 168: 399-407.
96. Allred BM, Lang JR, Barlaz MA, Field JA. Physical and biological release of poly- and perfluoroalkyl substances (PFASs) from municipal solid waste in anaerobic model landfill reactors. *Environ Sci Technol.* 2015; 49: 7648-7656.
97. Kwon BG, Lim HJ, Na SH, Choi BI, Shin DS, Chung SY. Biodegradation of perfluorooctanesulfonate (PFOS) as an emerging contaminant. *Chemosphere.* 2014; 109: 221-225.
98. Hamid H, Li LY, Grace JR. Formation of perfluorocarboxylic acids from 6:2 fluorotelomer sulfonate (6:2 FTS) in landfill leachate: Role of microbial communities. *Environ Pollut.* 2020; 259: 113835.
99. Liu Y, Robey NM, Bowden JA, Tolaymat TM, da Silva BF, Solo-Gabriele HM, et al. From waste collection vehicles to landfills: Indication of per- and polyfluoroalkyl substance (PFAS) transformation. *Environ Sci Technol Lett.* 2021; 8: 66-72.
100. Tseng N, Wang N, Szostek B, Mahendra S. Biotransformation of 6:2 fluorotelomer alcohol (6:2 FTOH) by a wood-rotting fungus. *Environ Sci Technol.* 2014; 48: 4012-4020.
101. Hamid H, Li LY, Grace JR. Aerobic biotransformation of fluorotelomer compounds in landfill leachate-sediment. *Sci Total Environ.* 2020; 713: 136547.
102. Zhang Y, Qv Z, Wang J, Yang Y, Chen X, Wang J, et al. Natural biofilm as a potential integrative sample for evaluating the contamination and impacts of PFAS on aquatic ecosystems. *Water Res.* 2022; 215: 118233.

103. Chen C, Fang Y, Cui X, Zhou D. Effects of trace PFOA on microbial community and metabolisms: Microbial selectivity, regulations and risks. *Water Res.* 2022; 226: 119273.
104. Li J, Zheng T, Yuan D, Gao C, Liu C. Probing the single and combined toxicity of PFOS and Cr(VI) to soil bacteria and the interaction mechanisms. *Chemosphere.* 2020; 249: 126039.
105. Ochoa-Herrera V, Field JA, Luna-Velsaco A, Sierra-Alvarez R. Microbial toxicity and biodegradability of perfluorooctane sulfonate (PFOS) and shorter chain perfluoroalkyl and polyfluoroalkyl substances (PFASs). *Environ Sci Process Impacts.* 2016; 18: 1236-1246.
106. Yin T, Chen H, Reinhard M, Yi X, He Y, Gin KY. Perfluoroalkyl and polyfluoroalkyl substances removal in a full-scale tropical constructed wetland system treating landfill leachate. *Water Res.* 2017; 15: 418-426.
107. Lu J, Lu H, Liang D, Feng S, Li Y, Li J. A review of the occurrence, monitoring, and removal technologies for the remediation of per- and polyfluoroalkyl substances (PFAS) from landfill leachate. *Chemosphere.* 2023; 332: 138824.
108. Appleman TD, Higgins CP, Quinones O, Vanderford BJ, Kolstad C, Zeigler-Holady JC, et al. Treatment of poly- and perfluoroalkyl substances in U.S. fullscale water treatment systems. *Water Res.* 2014; 51: 246-255.
109. Pauletto PS, Bandosz TJ. Activated carbon versus metal-organic frameworks: A review of their PFAS adsorption performance. *J Hazard Mater.* 2022; 425: 127810.
110. Kundu S, Patel S, Halder P, Patel T, Marzbali MH, Pramanik BK, et al. Removal of PFASs from biosolids using a semi-pilot scale pyrolysis reactor and the application of biosolids derived biochar for the removal of PFASs from contaminated water. *Environ Sci Water Res Technol.* 2020; 7: 638-649.
111. Zhang C, Jiang S, Tang J, Zhang Y, Cui Y, Su C, et al. Sorption of perfluoroalkylated substances (PFASs) onto granular activated carbon and biochar. *Environ Technol.* 2021; 42: 1798-1809.
112. Patel H, Greer M, Xia K, Wang Z, Brazil B, Liyanapatirana C, et al. Separation of dissolved organic matter (DOM) and per-and polyfluoro-alkyl substances (PFAS) from landfill leachate using modified coal fly- ash (CFA). *ChemRxiv*; 2022. doi: 10.26434/chemrxiv-2022-h8l06.
113. Zhang C, Jiang S, Tang J, Zhang Y, Cui Y, Su C, et al. Adsorptive performance of coal based magnetic activated carbon for perfluorinated compounds from treated landfill leachate effluents. *Process Saf Environ.* 2018; 117: 383-389.
114. Mayakaduwege S, Ekanayake A, Kurwadkar S, Rajapaksha AU, Vithanage M. Phytoremediation prospects of per- and polyfluoroalkyl substances: A review. *Environ Res.* 2022; 212: 113311.
115. Travar I, Uwayezu JN, Kumpiene J, Yeung LW. Challenges in the PFAS remediation of soil and landfill leachate: A review. *Adv Environ Eng Res.* 2021; 2: 006.
116. Awad J, Brunetti G, Juhasz A, Williams M, Navarro D, Drigo B, et al. Application of native plants in constructed floating wetlands as a passive remediation approach for PFAS-impacted surface water. *J Hazard Mater.* 2022; 429: 128326.
117. Chen Y, Zhang H, Liu Y, Bowden JA, Tolaymat TM, Townsend TG, et al. Concentrations of perfluoroalkyl and polyfluoroalkyl substances before and after full-scale landfill leachate treatment. *Waste Manage.* 2022; 153: 110-120.
118. Van der Bruggen B. Microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and forward osmosis. In: *Fundamental modelling of membrane systems.* Amsterdam, Netherlands: Elsevier; 2018. pp. 25-70.

- 119.Suhas PD, Sanna KN, Mallikarjuna N, Kakarla RR, Shyam SS, Tejraj MA. Membrane-based separation of potential emerging pollutants. *Sep Purif Technol.* 2019; 210: 850-866.
- 120.Huang S, Mcdonald JA, Kuchel RP, Khan SJ, Leslie G, Tang CY, et al. Surface modification of nanofiltration membranes to improve the removal of organic micropollutants: Linking membrane characteristics to solute transmission. *Water Res.* 2021; 203: 117520.
- 121.Tow EW, Ersan MS, Kum S, Lee T, Speth TF, Owen C, et al. Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates. *AWWA Water Sci.* 2021; 3: e1233.
- 122.Gao L, Yang G, Zhang J, Xie Z. De-ammonification using direct contact membrane distillation– An experimental and simulation study. *Sep Purif Technol.* 2020; 250: 117158.
- 123.Parani S, Oluwafemi OS. Membrane distillation: Recent configurations, membrane surface engineering, and applications. *Membranes.* 2021; 11: 934.
- 124.Robey NM, da Silva BF, Annable MD, Townsend TG, Bowden JA. Concentrating per- and polyfluoroalkyl substances (PFAS) in municipal solid waste landfill leachate using foam separation. *Environ Sci Technol.* 2020; 54: 12550-12559.
- 125.Burns SJ, Hinrichsen HM, Stevenson P, Murphy PJ. Commercial-scale remediation of per- and polyfluoroalkyl substances from a landfill leachate catchment using Surface-Active Foam Fractionation (SAFF®). *Remediation.* 2022; 32:139-150.
- 126.Smith SJ, Wiberg K, McCleaf P, Ahrens L. Pilot-Scale continuous foam fractionation for the removal of per-and polyfluoroalkyl substances (PFAS) from landfill leachate. *ACS ES T Water.* 2022; 2: 841-851.
- 127.Juva M, Trepanier A, Hamad F, Sunday-Lefkowitz L, Molina DN. Landfill leachate treatment targeting per- and polyfluoroalkyl substances [Internet]. Rochester, NY: Hajim School of Engineering & Applied Sciences; 2023 [cited date 2023 September 1]. Available from: <https://www.hajim.rochester.edu/senior-design-day/landfill-leachate-treatment-targeting-per-and-polyfluoroalkyl-substances/>.
- 128.Smith SJ, Lewis J, Wiberg K, Wall E, Ahrens L. Foam fractionation for removal of per- and polyfluoroalkyl substances: Towards closing the mass balance. *Sci Total Environ.* 2023; 871: 162050.
- 129.McQueen AD, Tedrow O. Demonstration of photocatalytic degradation of per-and polyfluoroalkyl substances (PFAS) in landfill leachate using 3D printed TiO₂ composite tiles. *Water Air Soil Pollut.* 2022; 233: 444.
- 130.Tian S, Xu T, Fang L, Zhu Y, Li F, Leary RN, et al. A ‘Concentrate-&Destroy’ technology for enhanced removal and destruction of per- and polyfluoroalkyl substances in municipal landfill leachate. *Sci Total Environ.* 2021; 791: 148124.
- 131.Singh RK, Brown E, Thagard SM, Holsen TM. Treatment of PFAS-containing landfill leachate using an enhanced contact plasma reactor. *J Hazard Mater.* 2021; 408: 124452.
- 132.Meegoda JN, Bezerra de Souza B, Casarini MM, Kewalramani JA. A review of PFAS destruction technologies. *Int J Environ Res Public Health.* 2022; 19: 16397.
- 133.Naicker KI, Kaweesa P, Daramola MO, Iwarere SA. Non-Thermal plasma review: Assessment and improvement of feasibility as a retrofitted technology in tertiary wastewater purification. *Appl Sci.* 2023; 13: 6243.
- 134.Ahmed MB, Alam MM, Zhou JL, Xu B, Johir MA, Karmakar AK, et al. Advanced treatment technologies efficacies and mechanism of per-and poly-fluoroalkyl substances removal from water. *Process Saf Environ Prot.* 2020; 136: 1-14.

135. Schaefer CE, Andaya C, Urtiaga A. Assessment of disinfection and by-product formation during electrochemical treatment of surface water using a Ti/IrO₂ anode. *Chem Eng J*. 2015; 264: 411-416.
136. Pierpaoli M, Szopinska M, Wilk BK, Sobaszek M, Luczkiewicz A, Bogdanowicz R, et al. Electrochemical oxidation of PFOA and PFOS in landfill leachates at low and highly boron-doped diamond electrodes. *J Hazard Mater*. 2021; 403: 123606.
137. Soriano A, Schaefer C, Urtiaga A. Enhanced treatment of perfluoroalkyl acids in groundwater by membrane separation and electrochemical oxidation. *Chem Eng J Adv*. 2020; 4: 100042.
138. Veciana M, Bräunig J, Farhat A, Pype ML, Freguia S, Carvalho G, et al. Electrochemical oxidation processes for PFAS removal from contaminated water and wastewater: Fundamentals, gaps and opportunities towards practical implementation. *J Hazard Mater*. 2022; 434: 128886.
139. Zhou Y, Zhang F, Tang L, Zhang J, Zeng G, Luo L, et al. Simultaneous removal of atrazine and copper using polyacrylic acid functionalized magnetic ordered mesoporous carbon from water: Adsorption mechanism. *Sci Rep*. 2017; 7: 43831.
140. Wang G, Xiao H, Zhu J, Zhao H, Liu K, Ma S, et al. Simultaneous removal of Zn²⁺ and p-nitrophenol from wastewater using nanocomposites of montmorillonite with alkyl-ammonium and complexant. *Environ Res*. 2021; 201: 111496.
141. Hamoud MA, Abo-Zahra SF, Attia MA, Someda HH, Mahmoud MR. Efficient adsorption of cesium cations and chromate anions by one-step process using surfactant-modified zeolite. *Environ Sci Pollut Res*. 2023; 30: 53140-53156.
142. Zhang J, Yan M, Sun G, Liu K. Simultaneous removal of Cu(II), Cd(II), Cr(VI), and rhodamine B in wastewater using TiO₂ nanofibers membrane loaded on porous fly ash ceramic support. *Sep Purif Technol*. 2021; 272: 118888.
143. Li J, Ren S, Qiu X, Zhao S, Wang R, Wang Y. Electroactive ultrafiltration membrane for simultaneous removal of antibiotic, antibiotic resistant bacteria, and antibiotic resistance genes from wastewater effluent. *Environ Sci Technol*. 2022; 56: 15120-15129.
144. Uebele S, Goetz T, Ulbricht M, Schiestel T. Mixed-matrix membrane adsorbers for the simultaneous removal of different pharmaceutical micropollutants from water. *ACS Appl Polym Mater*. 2022; 4: 1705-1716.