

ADVANCED FILTRATION SYSTEMS WITH MICRO-ADSORBENTS FOR MICROPOLLUTANT AND PFAS REMOVAL: PILE CLOTH MEDIA FILTRATION AND CERAMIC MEMBRANE FILTRATION

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Abstract

The increasing regulatory focus on organic micropollutants (OMP) and per- and polyfluoroalkyl substances (PFAS) requires advanced and resource-efficient (waste)water treatment technologies. Conventional systems based on (powdered) activated carbon are effective; however, due to kinetic limitations and competition with dissolved organic matter, they often involve high consumption and a large footprint in wastewater treatment plants for micropollutant removal. Two advanced filtration systems combined with adsorption-based treatment concepts using carbon-based micro-adsorbents ($d_{50} \sim 1 - 2 \mu\text{m}$) were investigated in different water matrices, including municipal wastewater, surface water, and groundwater. One process combined adsorption with flocculation and Pile Cloth Media Filtration (PCMF) using Ultrafiber Pile Cloth Media (PCM), operated at dosages of $\sim 5 - 15 \text{ mg/L}$ micro-adsorbent and short flocculation times $< 10 \text{ min}$, enabling efficient removal of micro-adsorbents as well as OMPs. The second process combined Ceramic Membrane Filtration with micro-adsorbents for the treatment of PFAS-containing ground and surface waters, operating at sorbent concentrations (in the sorbent reactor) of $20 - 30 \text{ g/L}$ and fluxes of $100 - 150 \text{ L/m}^2/\text{h}$. The results show that PCMF with Ultrafiber PCM provides effective removal of micro-adsorbents, achieving effluent turbidity levels of $\sim 1 - 2 \text{ NTU}$ without using a membrane process. Micro-adsorbents demonstrated strong potential to efficiently remove OMPs (up to $\sim 80 \%$ at $1.5 - 2 \text{ g/g DOC}$) as well as PFAS in different wastewater matrices, even at short contact times of $< 10 \text{ min}$. It was further shown that, similar to OMPs, PFAS removal also correlated with surrogate parameters such as UV absorbance reduction. The micro-adsorbent–Ceramic Membrane Filtration process demonstrates its potential to reduce PFAS from influent concentrations of up to several $\mu\text{g/L}$ (e.g., PFOS up to $3,559 \text{ ng/L}$) to below detection limits ($< 3 \text{ ng/L}$), thereby meeting drinking water standards, including for short-chain PFAS, while being characterized by low waste production. Both approaches exhibited synergistic effects between adsorption and separation processes, allowing shorter retention times, reduced sorbent demand, and minimized waste production.

Keywords

3D Woven Pile Cloth Media, Ultrafiber, Particle Removal, Activated Carbon, Wastewater Treatment, Surface Water Treatment, Groundwater Remediation

1. Introduction

The use of Powdered Activated Carbon (PAC) for organic Micropollutant (OMP) removal from municipal wastewater has been state of the art for more than 15 years. With the new European Urban Wastewater Treatment Directive, OMP removal will become mandatory for large wastewater treatment plants across the entire region in the upcoming years. In addition to OMP, Per- and Polyfluoroalkyl substances (PFAS) are also becoming a focus in the water treatment sector. Direct PAC dosing into the biological stage uses the existing volume for contact time but increases consumption due to competitive adsorption by organic matter [1]. In contrast, post-treatment application requires decoupling of hydraulic retention time (HRT) from adsorbent contact time. Given the growing importance of CO₂-footprint, space, and resource efficiency, more efficient processes are needed. Contact time, determined by adsorption kinetics, strongly influences reactor sizing and associated construction costs. With respect to adsorbent-based technologies, reducing the particle diameter leads to a further increase in adsorbent efficiency. Faster kinetics and a more efficient utilization of the adsorbent allow for a reduction of contact time and dosage, thereby contributing to a reduced CO₂, space and resource footprint. Previous studies have shown that decreasing the adsorbents particle size enhances adsorption kinetics [2-4]. This study evaluates two advanced filtration systems using carbon-based micro-adsorbents ($d_{50} \sim 1 - 2 \mu\text{m}$), each designed for distinct treatment scenarios. Pile Cloth Media Filtration (PCMF) [5-7] and membrane filtration [8, 9] are promising processes for the micro-adsorbents removal. These technologies exhibit synergistic effects, such as the simultaneous removal of soluble and particulate phosphorus, microplastics, and in the case of membrane-based systems additionally bacteria and (resistance) genes. PCMF in combination with micro-adsorbents is applied for the treatment of large flow rates and low to moderate concentrations of organic micropollutants as well as PFAS. In this combined process, no enrichment of the adsorbent occurs. The backwash water containing utilized micro-adsorbents is directed either to upstream treatment stages or to a separate thickening unit. For the retention of micro-adsorbents, Ultrafiber PCMs have proven to be particularly effective [5-7]. When using carbon-based micro-adsorbents in treatment plants, effective removal is essential to prevent the release of pollutant-loaded particles (OMPs/PFAS) into receiving waters. Residual carbon-based micro-adsorbents can be monitored via turbidity as a surrogate parameter [7], which is particularly relevant for the Micro-Adsorbent-PCMF process combination. The combination of micro-adsorbents and Ceramic Membrane Filtration (CMF) is intended for the treatment of low to moderate flow rates and medium to high concentrations of OMP and PFAS, whereby the adsorbents are retained in the system and loaded with micropollutants until just before breakthrough [9, 10]. Growing attention has been placed on OMP removal across WWTPs, but utilities and regulators are increasingly focused on how PFAS discharges from WWTPs influence downstream drinking water intakes. This shift is prompting questions about what PFAS concentrations are acceptable at the point of discharge, particularly where surface water or groundwater serves as a drinking water source. Conservative approaches suggest targeting drinking water regulations on sources which contribute to the drinking water supply. In

2024, the U.S. Environmental Protection Agency issued the Final National Drinking Water Regulation (NPDWR) to enforce compliance with six PFAS components within 5-years. This compliance period was later extended to 2031, with further consideration to the Maximum Contaminant Levels (MCL) for PFHxS, PFNA, GenX (HFPO-DA) and the Hazard Index. However, the MCLs for PFOS and PFOA will remain at 4 ng/L. With such low PFAS targets and uncertainty with final limits, combining CMF with Micro-Adsorbent technology can provide additional resiliency to meet the potential future demands.

This study presents two process concepts showing the application of micro-adsorbents for the removal of OMPs from the effluent of WWTPs and for the PFAS removal from contaminated groundwater and surface water. It demonstrates how the combination of adsorption, flocculation and filtration can be effectively applied to remove OMPs and PFAS from different water matrices.

2. Methods

The first system applying micro-adsorbents with PCMF was tested at three different municipal WWTPs, as well as one application for Surface Water Treatment Plant (SWTP). At three sites, pilot-scale plants equipped with a PCMF with a filter area of 0.5 m² (WWTP1), 2 m² (WWTP2) and 1 m² (SWTP) were investigated, while at one site a full-scale system with a PCMF filter area of 60 m² was studied (WWTP3). Filtration velocities ranged between 1 and 6 (9) m/h across the different sites. In the pilot-scale plants, OptiFiber UF-10 was used as Pile Cloth Media (PCM), while the full-scale system used OptiFiber PES-14. The pilot-scale PCMF sites included a drum filter, a pressurized drum filter, and a mini disk filter. The full-scale PCMF was a disk filter unit. The components of both the pilot-scale and full-scale systems included a dosing system, a flocculation reactor, and a PCMF unit (Mecana AG, Switzerland, or Aqua-Aerobic Systems, Inc., USA). In WWTP1, a UV probe was used additionally to control the dosing of micro-adsorbents. For dosing, either an inline mixer or a multidimensional Whirl-Field Mixing Injector (Ecowirl®, Econovation, Germany) was used to mix micro-adsorbent (5 – 15 (25) mg/L) and an iron-based coagulant (0.1 – 0.6 (0.8) g/g). In one of the pilot tests, micro-adsorbents were dosed together with the iron-based coagulant to enhance floc formation. The micro-adsorbent consisted of activated carbon-based material with a d₅₀ of 1 µm (WWTP1/2 and SWTP1) or 2 µm (WWTP1/3), supplied as a 10 % slurry and diluted in the pilot-scale systems as required for the experiments. Micro-adsorbent dosing was carried out using a peristaltic pump, while additives were introduced via a diaphragm dosing pump. The HRT in the flocculation ranged from ~ 0.5 – 10 min at pilot scale and was < 3 – 4 min in the full-scale system. Samples were collected in the inlet of the system as well as before and after the PCMF unit and analyzed for total suspended solids (TSS), turbidity, UV absorbance at 254 nm (UV_{254nm}), dissolved organic carbon (DOC), OMP, PFAS (according to EPA method), phosphorus fractions, and residual carbon-based micro-adsorbents. The analyzed OMPs were additionally evaluated as a sum (ΣOMP) [11], composed of benzotriazole, 4- and 5-benzotriazole, amisulpride, candesartan,

carbamazepine, clarithromycin, citalopram, diclofenac, hydrochlorothiazide, irbesartan, metoprolol, and venlafaxine. Depending on the site, 4 – 12 substances were considered based on their presence in the process influent.

The second system combines carbon-based micro-adsorbents with CMF and was applied for the treatment of PFAS-contaminated groundwater as well as surface water at three Water Treatment Plants (WTP). The pilot-scale unit consisted of a feed pump, dosing system, sorbent reactor, recirculation pump, backwash pump, and a CMF unit (Metawater Co., Ltd., Japan). The process mixes contaminated feed water with concentrated micro-adsorbents ($d_{50} \sim 1 \mu\text{m}$) in the sorption reactor to remove PFAS. The micro-adsorbent is then separated from the treated water by CMF, and the concentrated adsorbent-PFAS particles are recirculated to the reactor via cross-flow operation and an intermittent pressurized back-pulse step. The CMF had a nominal pore size of $0.1 \mu\text{m}$ and a filtration area of 0.04 m^2 (WTP2) respectively 0.4 m^2 (WTP1/3). Every separator module is integrity-tested (pressure decay) before starting the tests. The module operates in cross-flow mode, enabling effective adsorbent scouring and maintaining high permeability. Feed water enters the channels, where the crossflow velocity controls a separation layer on the inner walls. The filtrate passes through the membrane layer and exits through collection slits to the permeate side. The system was operated at a constant flux of $100 - 150 \text{ L/m}^2/\text{h}$, with micro-adsorbent concentrations of $20 - 30 \text{ g/L}$ in the adsorbent tank. To manage membrane fouling, back-pulse cleaning was performed every $15 - 20 \text{ min}$, with the discharge returned to the sorbent reactor. The contact time of the adsorbents in the tank was $\sim 10 \text{ min}$. For testing purposes, the process was operated beyond the expected breakthrough point to determine adsorption capacity. The adsorbent also acted as a scouring agent, maintaining high filterability at low pressure and producing solids-free effluent without producing waste for several weeks between sorbent replacements. The pilot plant consisted of two identical units, which could be operated either in parallel or in a two-stage configuration. Samples were collected at the system inlet and after the CMF unit and analyzed for turbidity, $\text{UV}_{254\text{nm}}$, Total Organic Carbon (TOC), DOC, and PFAS (according to EPA method).

3. Results and Discussion

3.1. Micro-Adsorbents-PCMF process

The focus of this study was, on the one hand, to demonstrate across different water matrices that PCMF can serve as an effective barrier for micro-adsorbents and, on the other hand, to investigate the performance of micro-adsorbents for the removal of OMPs and PFAS. First, the barrier function of single-stage PCMF systems with different PCMs and water matrices to be treated is discussed. Figure 1 shows the influent and effluent turbidity of the micro-adsorbent PCMF process for the investigated municipal WWTPs, with micro-adsorbent dosages varying between (5) 8 and 15 (20) mg/L . It can be observed that the effluent turbidity values of WWTP1 and WWTP2 are within a similar range of ~ 1 and 2 NTU , respectively, whereas WWTP3

exhibits an average turbidity of ~ 5 NTU. It should be noted that WWTP1 and WWTP3 are based on activated sludge processes, whereas WWTP2 operates with a biofilm process. As previously demonstrated in Fundneider, Kirchen [5] and Kirchen, Fundneider [6], an Ultrafiber PCM such as UF-10 is needed for efficient removal of micro-adsorbent. Pretreatment affects the operation as well as effluent quality of the PCMF via the introduced solids and their properties. Solids from biofilm systems (WWTP1) have a greater impact on downstream filtration (effluent quality) than those from activated sludge systems (WWTP2). Although the Microfiber PCM, such as PES-14 used in WWTP3, achieves turbidity removal of $\sim 89.7\%$, it exhibits a higher micro-adsorbent residual in the effluent (> 0.5 mg/L) compared to WWTP1 and WWTP2. A two-stage filtration process could provide a further improvement, with polishing using PCM UF-10 following PCM PES-14 to achieve low residual micro-sorbent concentrations in the effluent. Based on the correlation between turbidity and micro-adsorbent residual observed in Fundneider, Schäfer [12] and Kirchen, Fundneider [6], the effluent concentration in WWTP1 and WWTP2 can be estimated to be below $0.3 - 0.4$ mg/L. Consequently, the requirement for an activated carbon content of < 0.4 mg/L in the process effluent [13] would be met when using carbon-based micro-adsorbent at wastewater turbidity levels of < 3 NTU (WWTP1) and < 2 NTU (WWTP2).

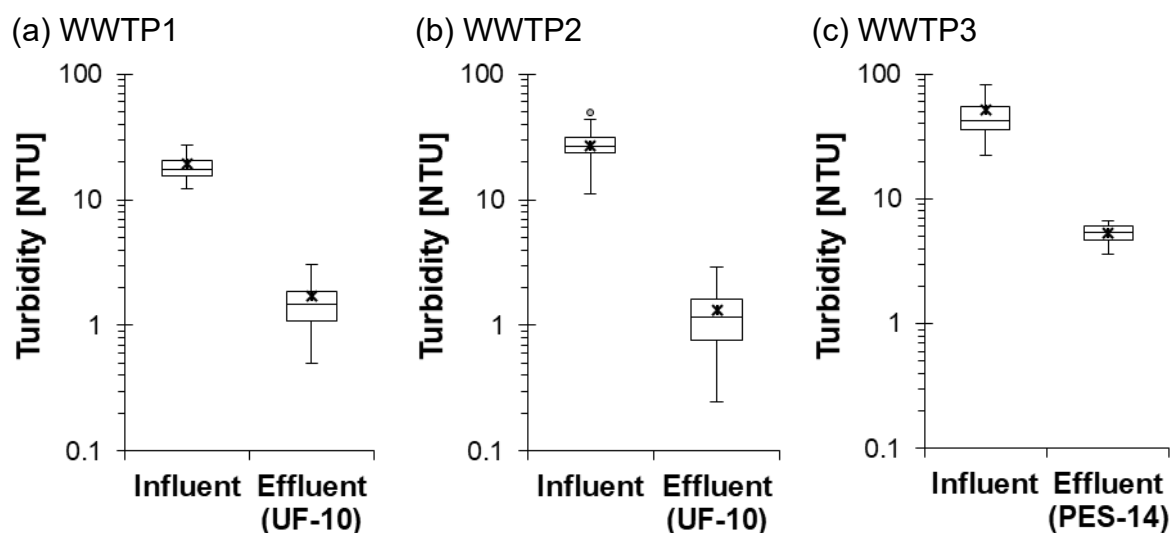


Figure 1: Turbidity in the influent and effluent of the Micro-Adsorbent PCMF process for WWTP1 with UF-10, WWTP2 with UF-10, and WWTP3 with PES-14 as Pile Cloth Media.

Ultrafiber PCMs improve micro-adsorbent removal by having smaller pore channels in the pile layer, enhancing the particle removal. However, compared to Microfiber PCMs, they reduce specific solids loading, resulting in increased backwash water amount at comparable solid loads. In addition to the appropriate PCM, flocculation of the micro-adsorbent also plays a crucial role. No polymers were applied in any of the WWTPs, and Kirchen, Fundneider [6] and Fundneider, Kirchen [14] clearly showed that a defined micro-adsorbent to metal salt ratio is essential for efficient removal by PCMF independent of the PCM. Higher iron-based coagulant dosages promote increased hydroxide formation, which positively affects removal but also leads to greater loading of the PCM, resulting in shorter cleaning intervals. It was found that homogeneous

micro-adsorbent distribution, proper mixing with the coagulant, and sufficient flocculation time (> 5 min to < 10 min before the PCMF) are critical factors. In this context, the Ecowirl proved advantageous over the conventional inline mixer due to the mixing of micro-adsorbent and iron-based coagulant within the vortex field. Considering the micro-adsorbent to metal salt ratio and its relationship to the micro-adsorbent residual, it was shown that increasing iron-based coagulant leads to lower micro-adsorbent residuals in the PCMF effluent [6], regardless of the WWTP [12]. However, higher metal salt dosages also result in increased solids loading on the PCMF. Each cleaning cycle disrupts the active filter layer of the PCM, which may negatively affect effluent quality. Similar micro-adsorbent to metal ratios ($\sim 0.3 - 0.6$ g Fe(III)/g micro-adsorbent) result in consistently high AC removal across all WWTPs. A positive side effect of adding iron-based coagulant dosages is the removal of soluble reactive phosphorus (sRP). In all WWTPs, it was shown that total phosphorus (TP) concentrations < 0.1 mg/L could be achieved by adding iron-based coagulant, with the sRP fraction minimized to the detection limit of 0.05 mg/L. The dominant fraction, aside from the non-reactive soluble phosphorus, was particulate phosphorus (pTP). TP and pTP concentrations were slightly higher when using PES-14 compared to UF-10, which goes hand in hand with the higher turbidity values, as also demonstrated in Kirchen, Fundneider [6]. Interestingly, the results of the micro-adsorbent with PCMF obtained for municipal wastewater can also be transferred to surface water (run-off). Low effluent turbidity was achieved even at lower micro-adsorbent to metal ratios ($0.2 - 0.4$ g/g), with micro-adsorbent dosages ranging from $10 - 20$ mg/L. The preselection of the micro-adsorbent to metal ratio was based on experiments conducted in WWTP1/2/3. Preliminary (small-scale) tests also confirmed that the use of UF-10 as PCM is necessary for effective micro-adsorbent separation.

Figure 2 shows the influent and effluent turbidity for SWTP at a dosage of ~ 10 mg/L. It becomes evident that, even in a water matrix primarily influenced by surface runoff from sealed and partially sealed areas, agglomeration and separation by PCMF result in average effluent turbidity's of ~ 0.8 NTU.

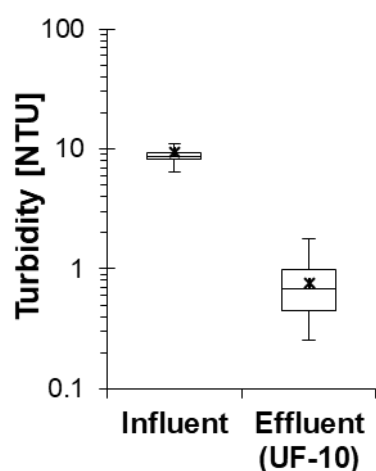


Figure 2: Turbidity in the influent and effluent of the Micro-Adsorbent PCMF process for SWTP with UF-10 as Pile Cloth Media.

The results demonstrate that the Micro-Adsorbent-PCMF process can be applied across a wide range of (waste)water matrices. The combination of adsorption, flocculation and filtration provides efficient removal of micro-adsorbent. The experiments further highlight that precise adjustment of the individual process steps, particularly flocculation and filtration, is crucial. The following section focuses on the adsorption performance of the applied micro-adsorbents.

Figure 3 shows the relative removal of (a) UV_{254nm} and (b) $\sum OMP$ as a function of the micro-adsorbent dose per gram of DOC for different WWTPs, as well as for the SWTP (shown only in (a)). It is evident that, when normalized to DOC, all WWTPs achieve comparable relative UV_{254nm} and $\sum OMP$ removal. Variability in relative removal can be attributed to the differing and sometimes short HRTs. A 30 – 35 % reduction in UV_{254nm} can already be achieved with $\sim 1 – 1.5$ g/g in WWTP2 and WWTP3. WWTP1 tends to show slightly lower removal at the same normalized micro-adsorbent dose, which is also observed for $\sum OMP$ removal. A similar magnitude of UV_{254nm} reduction can be observed in the SWTP, which is comparable to the results achieved in WWTPs. Despite lower influent DOC concentrations of $\sim 2.3 – 4.1$ mg/L, which are about a factor of 2 – 3 lower compared to the WWTP effluents, the observed UV_{254nm} reduction normalized to DOC is comparable.

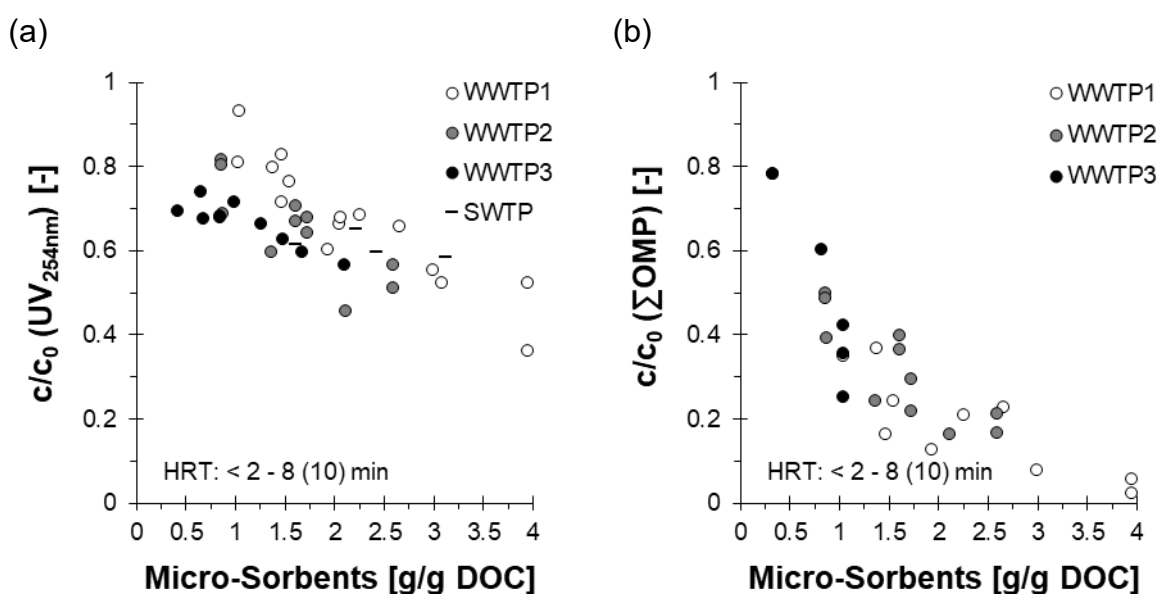


Figure 3: Relative removal (c/c_0) of (a) UV absorbance at 254 nm (UV_{254nm}) and (b) the sum of organic micropollutants ($\sum OMP$) as a function of the micro-adsorbent dose per g of dissolved organic carbon (DOC) for different WWTPs, as well as for the SWTP (shown only in (a)), at hydraulic retention times of < 2 – 8 (10) min.

For 80 % OMP removal (considering only the micro-adsorbent PCMF process, without upstream treatment stages), a dose of $\sim 1.5 – 2$ g/g is required. Increasing the HRT prior to the filter to 8 – 10 min allows for more efficient utilization of the micro-adsorbent (especially of adsorbents with $d_{50} \sim 2 \mu m$, see WWTP1/3), thereby enabling lower dosages as well as lower production costs of the micro-adsorbent. Nevertheless, as with PAC applications [15], the results demonstrate that normalization of the dosing to DOC allows for transferability of the findings, indicating that the insights can be applied to other treatment applications. In WWTP1-3, the focus was not on targeted PFAS

removal, as these systems treat municipal wastewater with an emphasis on OMP removal. In total, 24 different PFAS compounds were analyzed in WWTP1/3; however, only perfluorohexanesulfonic acid (PFHxS, WWTP1) and perfluorobutanesulfonic acid (PFBS, WWTP3) were detected. The remaining 22 PFAS compounds were below the detection limit in the effluents of WWTP1/3 ($< 2 - 5$ ng/L).

Figure 4 shows the relative removal of PFHxS and PFBS as a function of (a) the micro-adsorbent dose per g DOC and (b) the relative UV_{254nm} removal. Typically, 1 – 1.5 g of micro-adsorbents per g DOC are applied for OMP removal in WWTP effluents. At these dosages, PFHxS and PFBS removals of ~ 10 – 40 % were achieved. It should be noted that PFAS concentrations in the WWTP effluent were already in the range of 5 – 10 ng/L (WWTP1) and 20 – 30 ng/L (WWTP3). A similar relationship is observed between PFAS removal and the removal of the surrogate parameter UV_{254nm}. This indicates that PFAS removal correlates with UV_{254nm} reduction. At typical UV_{254nm} reduction of ~ 35 – 40 %, PFHxS and PFBS removals in the range of about 10 – 40 % are observed. Therefore, even in municipal wastewater, the relative UV_{254nm} removal can be used as an indicator to estimate PFAS removal performance. PFHxS (C6) and PFBS (C4), due to their medium- to short-chain character, are more difficult to remove using (non-specialized) carbon-based adsorbents. A direct comparison between the behavior of PFHxS and PFBS is only limited, as different wastewater matrices are involved. However, the results indicate that in predominantly municipal wastewater, the use of adsorption technologies leads to a synergistic removal of PFAS components in the fourth treatment stage alongside OMP removal. Considering the entire process, from the removal of organic contaminants by micro-adsorbent to its subsequent removal through flocculation and PCMF, the different sites have demonstrated the significant potential of this process.

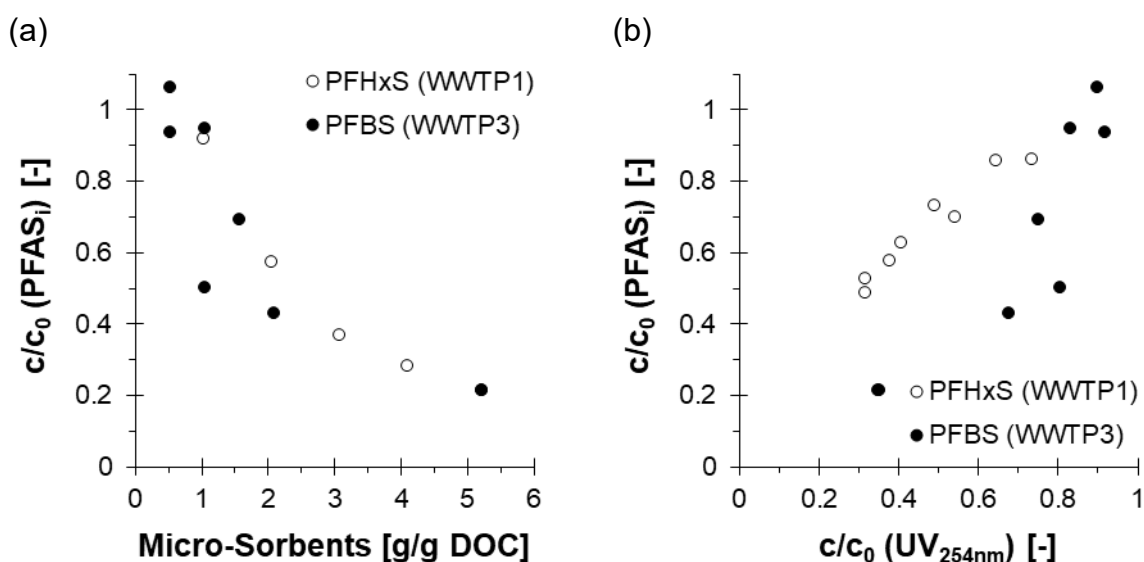


Figure 4: Relative removal (c/c_0) of perfluorohexanesulfonic acid (PFHxS, WWTP1) and perfluorobutanesulfonic acid (PFBS, WWTP3) as a function of (a) the micro-adsorbent dose per g dissolved organic carbon (DOC) and (b) the relative UV absorbance at 254 nm (UV_{254nm}) removal.

Despite the short HRT prior to PCMF, the micro-adsorbent requirement is lower than in processes with PAC dosing upstream of a filter [1, 16]. The shorter HRT also results

in a significantly smaller footprint compared to comparable PAC-based processes, as the volume of the contact reactors can be reduced due to accelerated adsorption kinetics. The backwash water amount in the PCMF was observed in all WWTPs as well as in the SWTP using UF-10 to be ~ 5 – 8 % of the incoming feed for a micro-adsorbent dosage of 10 – 12 mg/L, a micro-adsorbent to metal ratios of 0.4 – 0.6 g/g, and a filter velocity of 5 – 6 m/h. Further optimization is possible, for example, through separate thickening of the backwash water to reduce volume and/or by recycling of used micro-adsorbent to upstream processes to utilize any remaining adsorption capacity. The energy demand of the process, including micro-adsorbent production and operation of the PCMF with UF-10, is ~ 27 Wh/m³ at a micro-adsorbent dosage of 10 mg/L ($d_{50} \sim 1 \mu\text{m}$) and a filter velocity of 5 m/h [6]. Overall, the energy demand of the micro-adsorbent PCMF process is considerably lower than that of membrane processes and is comparable to conventional OMP removal processes [17, 18]. Nevertheless, the following example using the combination of micro-adsorbents and CMF is intended to demonstrate the potential of membrane processes in a representative application area.

3.2. Micro-Adsorbents-CMF process

The CMF incorporates a specialized 0.1 μm separation surface engineered to support high sorbent concentrations, resist abrasion, accommodate smaller sorbent particle sizes, and maintain high specific permeability. This creates an absolute barrier to reject all the micro-adsorbent at concentrations as high as 40 g/L. Table 1 summarizes the PFAS concentrations, hazard index, sorbent load, and replacement interval (for adsorbent) of the CMF and micro-adsorbent system in compliance with the NPDWR at three WTPs.

Table 1: CMF and Micro-Adsorbent Compliance with U.S. EPA National Primary Drinking Water Regulations (NPDWR) on tests performed at three Water Treatment Plants (WTP). Influent and effluent concentrations of perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS), perfluorononanoic acid (PFNA), hexafluoropropylene oxide dimer acid (HPFO-DA), and perfluorobutane sulfonate (PFBS) are presented together with the hazard index, sorbent load, and sorbent replacement interval (SRI).

#		NPDWR	WTP1		WTP2		WTP3	
		MCL	Surface water		Ground Water		Surface Water	
			Influent	Effluent	Influent	Effluent	Influent	Effluent ⁽²⁾
PFOA	ng/L	4.0	10.1	BDL	28	BDL	248	BDL
PFOS	ng/L	4.0	7.8	BDL	80	BDL	3,559	BDL
PFHxS	ng/L	10	1.1	BDL	8.6	BDL	1,028	BDL
PFNA	ng/L	10	0.3	BDL	1.4	BDL	BDL	BDL
HPFO-DA	ng/L	10	BDL	BDL	BDL	BDL	BDL	BDL
PFBS	ng/L	2000	9.3	9.6	47	8.6	163	13
Hazard Index ⁽¹⁾	-	1	-	0	-	0	-	-
Sorbent Load	g/L	-	20		30		40	
SRI	d	-	28		16		7	

(1) Hazard Index is a mixture of compounds determined by: $\sum[(\text{PFHxS}/10) + (\text{PFNA}/10) + (\text{PFBS}/2000) + (\text{HPFO-DA}/10)]$

(2) After Stage 2

MCL Maximum Contaminant Level

BDL Below Detection Level

The following sections provide a detailed discussion of each WTP. WTP 1 draws surface water from a nearby creek and treats it conventionally with coagulation, sedimentation and filtration. With the use of a granular activated carbon layer on the existing filter, the facility was not able to reduce PFAS to the required MCLs. Testing conducted using the CMF and micro-adsorbent combination was able to demonstrate PFAS levels below detectable levels for four weeks prior to breakthrough of PFBS. Performance was sustained well below the 4 ng/L limit for PFOS and PFOA and in full compliance with the anticipated MCLs. Unique to this arrangement was the absence of wasted material during 28-day replacement interval. Upon the tests conclusion, the system produced a rate of 1 L of waste per 27 m³ of treated water. WTP 2 is located in the Southeastern US and treats groundwater that is stored in a nearby pond. Testing was conducted over a 90-day period, with sorbent replacements determined by the presence of detectable PFBS, despite being well below the 2,000 ng/L limit. All other parameters remained below detectable levels prior to sorbent replacement at the 16-day mark. This replacement schedule resulted in a waste production of 1 L of waste per 23 m³ of treated water. The customer proceeded with the installation of a full-scale, 34 m³/h system that has exhibited equivalent performance. At WTP 3, the CMF and micro-adsorbent configuration is well suited for treating challenging matrices with elevated PFAS concentrations. This evaluation was performed under the U.S. Department of Defense Environmental Security Technology Certification Program. The source water was a stream impacted by aqueous film-forming foam, typically exhibiting turbidity levels of 2 – 4 NTU and TOC of 1 – 2 mg/L. Periodic storm events caused turbidity spikes exceeding 100 NTU, requiring the use of PCMF with PES-14 PCM to maintain effluent turbidity < 4 NTU. To achieve drinking water quality effluent, a two-stage CMF system was implemented. The first stage removed the majority of PFAS, TOC, and suspended solids, enabling the second stage to consistently meet the treatment objectives. Due to the complexity of the water matrix, the sorbent slurry required replacement approximately once per week.

Figure 5 shows the relative removal and effluent concentrations of PFOS, PFOA, PFBS, PFHxS, and total PFAS as a function of the micro-adsorbent dose per g of DOC at WTP3 for the two-stage micro-adsorbent CMF process. Despite the low influent DOC concentrations of 1 – 2 mg/L, the micro-sorbent doses (g/g DOC) required for PFAS removal are significantly higher than those observed in previous studies on OMP removal. It should be noted that OMP removal typically focuses on achieving ~ 80 % removal rather than effluent concentrations, whereas for PFAS the primary focus is on effluent concentrations. Total PFAS is removed by ~ 97 % in the first stage at a dose of 100 g/g DOC and by ~ 50 % in the second stage. The two-stage process demonstrates that, even under high influent PFAS concentrations, low effluent levels of PFOS, PFOA, PFBS, and PFHxS can be achieved in the second stage at relatively low micro-sorbent doses of ~ 40 g/g DOC (after an initial dose of ~ 12 g/g DOC in the first stage).

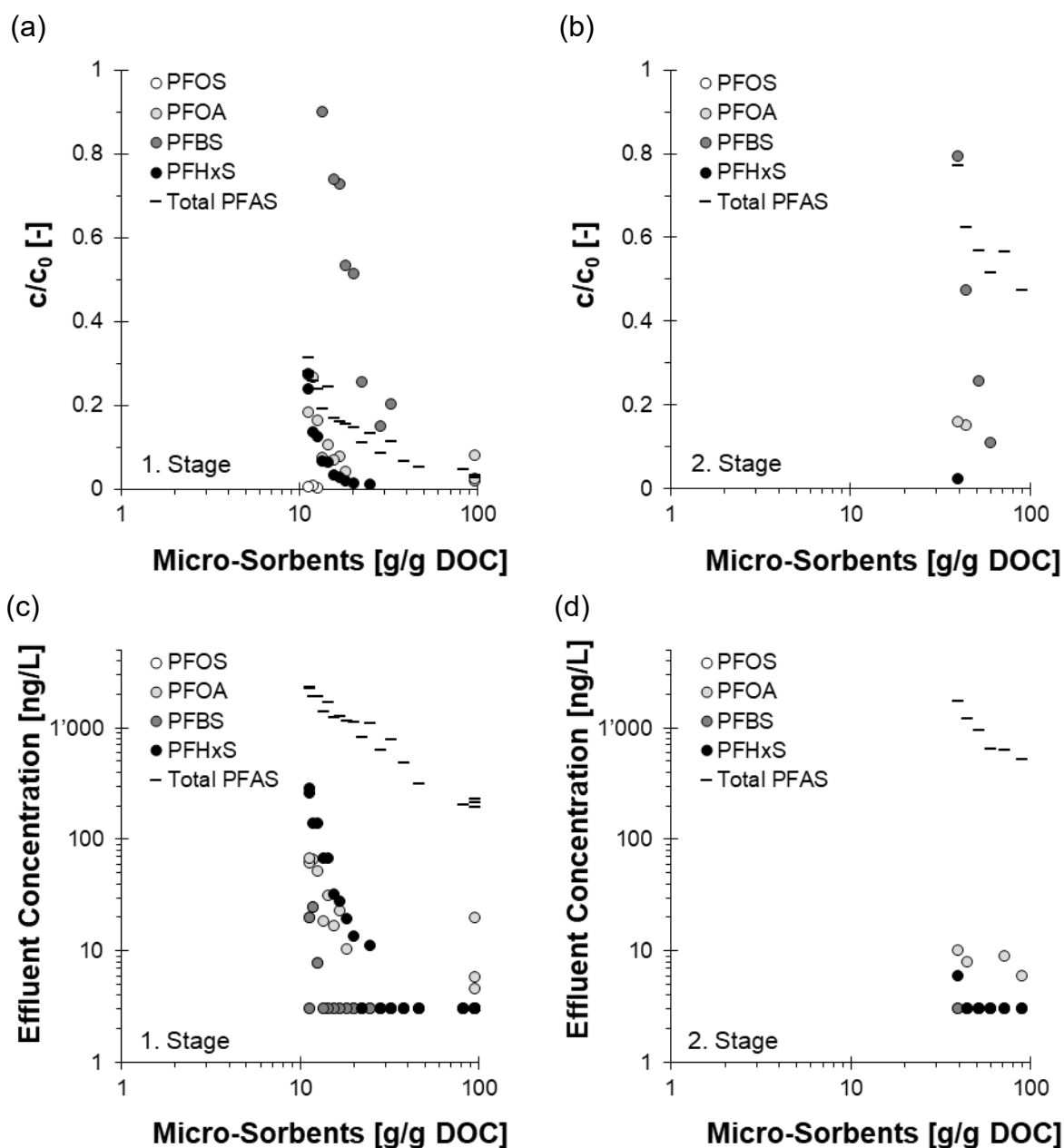


Figure 5: (a, b) Relative removal (c/c_0) and (c, d) effluent concentration of perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA), perfluorobutane sulfonate (PFBS), perfluorohexane sulfonate (PFHxS), and total PFAS as a function of the micro-adsorbent dose per g of dissolved organic carbon (DOC) at WTP3. (a, c) present the results of the first stage and (b, d) the results of the second stage of the micro-adsorbent CMF process.

The results clearly show that the CMF and micro-adsorbent concept is a highly effective process for PFAS removal. It also demonstrates that CMF has the potential to significantly reduce residual waste compared to PCMF, thereby minimizing the associated disposal costs for PFAS-loaded micro-adsorbents. In particular, WTP1 and WTP2 showed a waste generation of 0.037 – 0.043 ‰, which is considerably lower compared to PCMF (in a different application context).

4. Conclusions

The studied processes demonstrate that micro-adsorbents in combination with advanced filtration systems are a highly effective solution for removing OMPs and PFAS from a wide range of water matrices. The PCMF with Ultrafiber PCM achieved stable micro-adsorbent removal with effluent turbidities in the range of $\sim 1 - 2$ NTU, enabling micro-adsorbent effluent concentrations below $\sim 0.3 - 0.4$ mg/L under optimized pretreatment conditions. Furthermore, OMP removal $> 80\%$ were achieved at dosages of $\sim 1.5 - 2$ g/g and HRT < 10 min prior to filtration. The Micro-Adsorbents-CMF process demonstrated high PFAS removal and operated stably with backwash intervals of $15 - 20$ min. Across the investigated water treatment plants, PFAS concentrations were reduced from influent levels up to several $\mu\text{g/L}$ to below detection limits in the treated effluent in the best-performing configurations. Replacement intervals ranged from $\sim 7 - 28$ d depending on water matrix complexity and sorbent loading, while waste generation was significantly reduced, substantially lower than conventional systems. Overall, both advanced technologies benefit from strong synergies between adsorption, (flocculation) and separation, resulting in a compact process design, reduced sorbent requirements and improved resource efficiency. Both systems offer a promising approach to the removal of OMPs and PFAS, including short-chain PFAS, whilst minimizing waste and footprint.

5. References

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