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Influencing biological activity for the removal of organic micropollutants in granular activated carbon filters

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ABSTRACT

The biological activation of granular activated carbon (GAC) filters extends their service life until a threshold of 80% is reached for the removal of organic micropollutants (OMP). To quantify the influence of biological activity on OMP removal, the 12 indicator substances of the 2024 revised EU Urban Wastewater Treatment Directive were used. Five years of pilot testing were examined, presenting data from three GAC filters under various process settings. Hydraulic parameters (empty bed contact time (EBCT) and filtration velocity (v_{filtr})) and the backwash frequency were investigated. The pilot-scale GAC filters were fed with effluent from the wastewater treatment plant Nette (86,000 p.e.), which was subsequently further treated by a pilot-scale ultrafiltration system. The suspended solids-free feed was, alongside the process settings and temperature, a further influencing factor that was investigated regarding its effects on biological activity and thus on OMP removal.

The results show that biologically active GAC filters achieve consistently high removal efficiency (>90%) for highly biodegradable OMPs even after >115,000 BV (CUR <4.0 mg_{AC}/L). However, biological activation also extends the filter service life for poorly biodegradable OMPs (e.g. carbamazepine). This could indicate a partial bioregeneration of the GAC. With appropriate process settings, biodegradation begins to compensate for the declining adsorption capacity at around 10,000–15,000 BV. The effect of backwashing diminishes as the filter service life increases and is expected to play a crucial role during the early growth phases. EBCT and v_{filtr} can limit the biodegradation of OMPs, thereby preventing the biological activity from being fully exploited.

1. Introduction

The EU Urban Wastewater Treatment Directive (EU UWWTD), revised in 2024, calls for further removal of organic micropollutants (OMPs) from the effluent of wastewater treatment plants (WWTPs) with a population equivalent (p.e.) of more than 150,000 and plants that discharge into particularly sensitive water bodies. In addition to oxidative processes such as ozonation, adsorption processes using activated carbon are primarily used to remove OMPs from the effluent of full-scale WWTPs. One application of activated carbon is in granular activated carbon filters (GAC filters), which are used as a downstream polishing stage (Tarigan et al. 2025). In addition to adsorptive removal, biodegradation processes were observed to impact the breakdown of OMPs in GAC filters, particularly during long filter service life respectively high bed volumes (BV) (Fundneider et al. 2021b, Sauter et al. 2023, Sbardella et al. 2018). Consequently, the biological activation of GAC filters shows the potential to extend their service life until the 80% OMP removal threshold specified by the UWWTD is reached (Larasati et al. 2026). However, the growth of biomass in GAC filters can also cause pore blockages and lead to an increased pressure drop across the depth of the filter bed (Fundneider et al. 2021b, Hess and Morgenroth 2021). Moreover, the influence of biological activity on the OMP removal in GAC filters remains poorly understood, since it is difficult to distinguish between the effects of adsorption and biodegradation (Betsholtz et al. 2024). A better understanding of the biological activity itself is therefore the first step towards better understanding its influence on the removal of OMPs.

The biological activation of GAC filters is generally based on dissolved organic matter (DOM), which serves as a substrate source at concentrations orders of magnitude higher than those of OMPs (Çeçen

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and Aktas 2012). As a result the biodegradation of OMPs is predominantly regarded as a co-metabolic process of biological DOM removal (Ngo et al. 2020, Thuptimdang et al. 2020). Overall, the development of biomass in GAC filters can be divided into three phases. In the induction phase a range of different microorganisms settle, forming a biofilm on the rough outer surface of the activated carbon (Korotta-Gamage and Sathasivan 2017, Liao et al. 2015). In the second phase, the growth phase, biological activity continues to increase until a plateau is reached (Simpson 2008). In the third phase, the plateau phase, biofilm growth is limited by substrate transport and nutrient availability (Fundneider 2020). Findings in Graß et al. (2025) suggest that DOM removal during the plateau phase is limited by the bioavailable DOM fraction in the effluent of municipal WWTPs. Accordingly, DOM removal is hardly subject to seasonal fluctuations in biologically active GAC filters, as observed in several studies (Emelko et al. 2006, Fundneider et al. 2021b, Graß et al. 2025).

However, in all three phases of biomass development biological activity depends not only on environmental conditions (nutrient and O_2 supply, and temperature) but also on operating parameters (empty bed contact time (EBCT), filtration velocity (v_{filtr}), and backwashing) (Basu et al. 2015). Above all, backwash frequency is the operating parameter through which biofilm thickness is regulated (Fundneider et al. 2021b, Liao et al. 2015). Backwashing is often initiated when a defined pressure drop is reached over the filter bed depth. Thus, backwash frequency is influenced primarily by the type of pre-treatment, as well as by nutrient concentrations and the effluent temperature. Backwash frequency of GAC filters operated in wastewater treatment ranges approximately from 0.1 to 1.5 backwashes per week (Worch 2021). According to Fundneider et al. (2021b), backwash frequency serves as a suitable indicator for biofilm development in GAC filters provided that the feed entering the filters is free of suspended solids.

However, the EBCT is the key parameter in GAC filter dimensioning and describes the time during which the liquid phase and the activated carbon are in contact. The EBCT is a purely theoretical parameter calculated from v_{filtr} and the filter bed height (h_f), disregarding the packing density (φ_F) of the GAC in the filter (Worch 2021). According to Krückels et al. (1976), the breakthrough curve of GAC filters does not depend on v_{filtr} or h_f, but is determined purely by the resulting EBCT. In general, the utilisation of the adsorption capacity increases with rising EBCT (Fundneider et al. 2021a, Zietzschmann et al. 2014). This applies particularly to EBCT values up to 20-30 min. Above this, the adsorption capacity does not increase further (Fundneider et al. 2021a). However, according to Larasati et al. (2026), a minimum EBCT of 26 min is required to achieve 80% removal of 20 investigated OMPs in biologically active GAC filters (> 400,000 BV). Of the 12 indicator substances listed in the UWWTD, only amisulpride was not included in the study by Larasati et al. (2026). Consequently, adsorption processes and biological degradation processes place different demands on the EBCT of GAC filters. Furthermore, parameters such as temperature or filter service life influence adsorption and biodegradation processes in various ways. Whilst the adsorption capacity decreases as the number of BV increases (Worch 2021), biological activity builds up or remains at a constant level once the plateau phase is reached (Fundneider 2020). Regarding the influence of temperature, OMPs exhibit either exothermic or endothermic adsorption behaviour in GAC filters, depending on their substance properties (Graß et al. 2026). On the other hand, biological activity in wastewater treatment generally increases with increasing temperatures (Chen et al. 2020).

This study comprehensively examines both the influence of different process settings and external factors on GAC filter performance. Based on an extensive dataset from a 5-year pilot study, new insights into the biological activation of GAC filters are provided. These include the breakthrough behaviour of all OMPs listed in the EU UWWTD under varying hydraulic conditions (EBCT, v_{filtr}) and backwash frequencies. Moreover, special emphasis is placed on the impact of UF pretreatment on achievable filter service life of GAC filters. Consequently, this study not only provides new scientific insights into the interaction between biological activation and OMP removal, but also offers practical details for the long-term operation of GAC filter systems.

2. Materials and methods

2.1. Experimental setup

2.1.1. General layout of the pilot plant

A pilot plant comprising an UF system and three downstream GAC filter columns was operated for five years (January 2021 – December 2025) in the effluent of the WWTP Nette (86,000 PE) in North Rhine-Westphalia, Germany. The full-scale WWTP Nette carried out mechanical (screens, sand and grease traps and primary clarification) and biological (conventional activated sludge system (CAS) with pre-anoxic denitrification) pre-treatment before the wastewater was fed into the pilot plant system. The WWTP Nette is further equipped with a non-biologically active flocculation filtration (24 continuously rinsed Dyna-Sand filters) downstream of the secondary clarification). The first part of the pilot plant was an UF system (ZeeWeed 500®) with outside-in supported PVDF hollow fibre membranes. The three GAC filter columns were all filled with the same GAC (Chemviron Cyclecarb® 401) and had identical filter designs (filter bed height (h_f=2.1 m; filter surface area (A_f) = 0.046 m^2). The filters were all fed from top to bottom, and the flow rate through the filters was kept constant over time by adjusting the inlet pressure. Whilst filter A was the reference filter, filter B differed from filter A in terms of its backwash interval, and filter C differed from filter A in terms of its feed rate. Fig. 1 shows the flow chart of the pilot-scale UF and GAC filtration. The sampling points (SP) relevant to this study are marked by red dots in the flow chart. The main process parameters, which were kept constant for the majority of the trial period (30.11.21 to 24.10.24), are additionally marked. Further studies have examined other aspects of the pilot plant. An overview of these can be found in the SI (Chapter 1.1).

2.1.2. Experimental procedure and process settings

The key design and main operating parameters (30.11.21 to 24.10.24) are shown in Fig. 1 and listed in Table 1 of the Supplementary Information (SI). Unlike the process settings shown in Fig. 1, both the backwash interval for filter B and the feed rate for filter C were adjusted at various stages during the course of the project. Overall, the project duration can be divided into the following four project phases (pp):

pp 1 (15 January 2021 to 30 November 2021): Commissioning of the pilot plant

- No backwashing of the GAC filters
- Changeover of the feed to filter B from dynamic to static (June 2021)

pp 2 (30 November 2021 to 24 October 2024): Largely stable pilot-plant operation

- Regular backwashing and static feeding
- Process settings as shown in Fig. 1

pp 3 (24 October 2024 to 24 July 2025): Effect of intensified backwashing

- Increase in the backwashing interval for filter B from weekly to daily
- Remaining process settings as shown in Fig. 1

pp 4 (24 July 2025 to 8 December 2025): Impact of adjusted EBCT

- Continued daily backwashing of filter B
- Increase in the EBCT for filter C from 20 to 30 min
- Remaining process settings as shown in Fig. 1

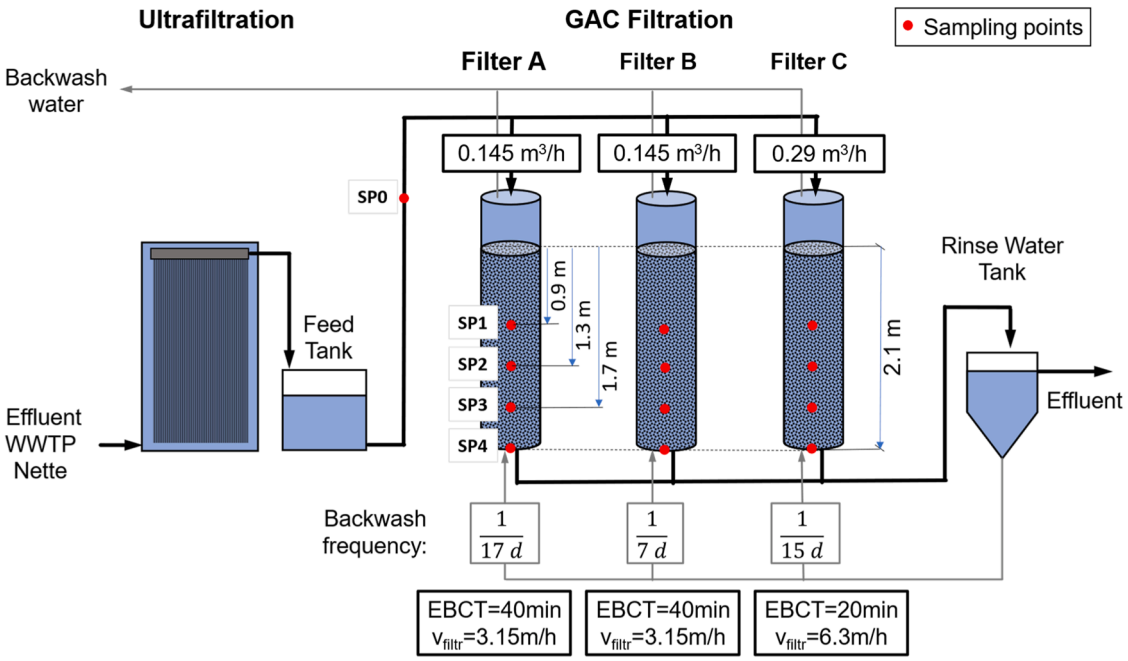


Fig. 1. Flow chart of the pilot-scale UF and GAC filtration system. Sampling points (SP0 to SP4) are marked with red dots.

The backwash frequency of filter A and filter C was controlled on a pressure-dependent basis, whilst the backwash frequency of filter B was controlled on a time-dependent basis. Pressure-dependent backwashing was carried out manually when a pressure drop of over 100 mbar was measured over the filter bed depth.. The time-dependent backwash frequency for filter B was weekly in pp 2 and was increased to a daily backwash in pp 3 and pp 4. The total number of backwashes over the project duration for all three GAC filter columns is shown in Fig. 1 of the SI.

Filter B (weekly/daily backwashing) has the highest number of backwashes throughout the entire project. Filters A and C follow largely parallel trends until early 2023. Thereafter, the pressure-dependent control system resulted in progressively shorter backwash intervals for filter C compared with filter A. The difference in backwash interval between the three GAC columns is shown in Fig. 2 of the SI.

Since the feed rate of filter C was twice that of filter A, filter C processed roughly twice the amount of BV at the same time as filter A. However, SP1 in filter A (EBCT of 17 min) and SP3 in filter C (EBCT of 16 min) show a largely parallel temporal course of BV. Fig. 3 in the SI shows the timeline of BV of filter A and filter C in all four sampling points (SP1 to SP4). In pp 4 the feed rate to filter C was reduced such that the EBCT in SP4 increased from 20 min to 30 min and the v_{filtr} decreased from 6.3 m/h to 4.2 m/h.

2.2. Sampling and chemical analysis

2.2.1. Wastewater sampling from the pilot plant

O_2 concentrations at the inlet (SP0) and outlet (SP4) of the three GAC filters were measured approximately once a week. Ammonia nitrogen (NH_4-N) chemical oxygen demand (COD) and DOC were sampled at the inlet (SP0) and outlet (SP4) of the GAC filters every three weeks. OMPs were also sampled every three weeks at the inlet (SP0) and outlet (SP4) of the GAC filters, as well as at the intermediate sampling points (SP1 to SP3). Samples at SP0 and SP4 were taken using automatic samplers (23-h composite samples), whilst the samples at SP1 to SP3 were taken manually (qualitative samples). 23-h composite samples (11am to 10 am) were chosen so that, on consecutive sampling days, there was time to take the sample and restart the sampler correctly.

2.2.2. Sample analysis

When the pilot plant first came into operation, the removal of OMPs was monitored on the basis of six indicator substance listed and published by the state of North Rhine-Westphalia (NRW) in 2016: 1H-benzotriazole, carbamazepine, metoprolol, clarithromycin, diclofenac and sulfamethoxazole. From 21 February 2023, the monitoring list was expanded to include the OMPs still missing from the indicator substances list set out in the 2024 revision of the EU UWWTD (European Union 2024): Σ4-/5-methylbenzotriazole, amisulpride, candesartan, citalopram, hydrochlorothiazide, irbesartan and venlafaxine. Table 3 in the SI shows the indicator substances for the monitoring of OMP removal in accordance with the NRW list of 2016 and the 2024 revised EU UWWTD (European Union 2024). Furthermore, the corresponding OMPs of the EU UWWTD are categorised according to their biodegradability in GAC filters, based on the results published in (Graß et al. 2026). OMPs that are poorly to moderately biodegradable in GAC filters include: 1H-benzotriazole, candesartan, carbamazepine, ∑4-/5-methylbenzotriazole, irbesartan and venlafaxine. OMPs that are readily biodegradable in GAC filters include: citalopram, hydrochlorothiazide, metoprolol, clarithromycin, diclofenac and amisulpride. The OMPs were measured using LC-MS (DIN 38407-47:2017-07) with a Limit of Quantification (LOQ) of 0.02 µg/L. For data evaluation, values smaller than the LOQ (<LOQ) were set at half the LOQ. This follows the recommendation by Choubert et al. (2017) regarding the handling of values <LOQ. From an analytical point of view, this compromise is preferable to setting the LOQ itself for values <LOQ (Choubert et al. 2017). DOC was analysed by using a total organic carbon analyser (SHIMADZU; TOC-L). All samples were filtered through 0.45 µm syringe filters (Labsolute ProFill, RC, Ø = 25 mm) prior to DOC analysis. O_2 was measured on site using a multi-parameter handheld meter (WTW; Multi 3510 IDS). COD was determined in accordance with DIN 38409 H41:1980-12, with a detection limit of 15 mg/L. Ammonium nitrogen (NH_4-N) was determined following DIN-EN-(ISO) 11732:2005-05, with a detection limit of 0.1 mg/L. Nitrite-N (NO_2-N) and nitrate-N (NO_3-N) were analysed by ion chromatography (in accordance with DIN EN ISO 10304-1:2009-07) with limits of quantification of 0.03 mg/L and 0.12 mg/L respectively. Total phosphorus (TP) was analysed photometrically in agreement with EN ISO 6878, with a limit of quantification of 0.05 mg/L.

2.3. Calculation methods and statistical analysis

2.3.1. Nutrient balancing

To assess the measured nutrient removal in the three GAC filters, nutrient balances were calculated based on carbon-to-nitrogen and carbon-to-O_2 ratios derived from the Activated Sludge Model 1 (ASM1) (Henze et al. 2006). The O_2, NH_4-N, NO_2-N, NO_3-N and TP measurements were then used to estimate the amount of biologically degraded carbon in the filters. As carbon compounds can be removed both by adsorption and biologically in the GAC filters, the nutrient balances can be used to divide the total carbon removal into an adsorbed fraction and a biologically degraded fraction. This breakdown is a rough estimate, based on the assumption that all the O_2 removed in the GAC filters is used for biomass growth. As a first step of the nutrient balances, the amount of O_2 consumed for the growth of autotrophic biomass (X_A) was estimated based on the NH_4-N degraded. Eq. (1) shows the corresponding calculation of the O_2 load consumed by nitrification:

$$O2_{Nitri} = \left(c_{0,NH4-N} - c_{i,NH4-N}\right)\frac{g_{NH4-N}}{m^3} * Q_i\frac{m^3}{d} * \frac{18\frac{g_{O2}}{g_{XA}}}{4.25\frac{g_{NH4-N}}{g_{O2}}}\left[\frac{g_{O2}}{d}\right] \quad (1)$$

c_0: Influent concentration
c_i: Concentration at sampling point i (SP1 to SP4)
Q_i: Feed rate

In the second step (Eq. (2)), the NO_2-N and NO_3-N—collectively referred to as SNO—are calculated. These consist of the portion of SNO generated by the formation of XA (nitrification) and the portion of SNO removed from the feed to the GAC filters.

$$SNO_{Deni} = O2_{Nitri} * \frac{4.17\frac{g_{SNO}}{g_{XA}}}{4.25\frac{g_{O2}}{g_{XA}}} + \left(c_{0,SNO} - c_{i,SNO}\right)\frac{g_{SNO}}{m^3} * Q_i\frac{m^3}{d}\left[\frac{g_{SNO}}{d}\right] \quad (2)$$

The proportion of the O_2 load remaining after nitrification is attributed in the balance to the aerobic accumulation of X_H. Eq. (3) shows the calculation of the aerobic accumulation of X_H based on O_2 consumption:

$$XH_{aerob} = \left(\left(c_{0,O2} - c_{i,O2}\right)\frac{g_{O2}}{m^3} * Q_i\frac{m^3}{d} - O2_{Nitri}\right) * \frac{1}{0.67\frac{g_{O2}}{g_{XH}}}\left[\frac{g_{XH}}{d}\right] \quad (3)$$

In addition, a carbon balance can be established based on the above equations. To do this, the calculated amount of carbon required for the aerobic formation of X_H is subtracted from the total measured COD elimination. Eq. (4) shows the calculation of the aerobically biodegraded COD (substrate – S):

$$COD_{bio,aerob} = \left(\left(c_{0,O2} - c_{i,O2}\right)\frac{g_{O2}}{m^3} * Q_i\frac{m^3}{d} - O2_{Nitri}\right) * \frac{1.64\frac{g_S}{g_{XH}}}{0.67\frac{g_{O2}}{g_{XH}}}\left[\frac{g_{COD}}{d}\right] \quad (4)$$

The total biologically degraded COD (COD_{bio}) consists of $COD_{bio,aerob}$ and the COD degraded anoxically during denitrification ($COD_{bio,anox}$). Eq. (5) shows the calculation of COD_{bio}:

$$COD_{bio} = COD_{bio,aerob} + SNO_{Deni} * \frac{1.64\frac{g_S}{g_{XH}}}{0.22\frac{g_{SNO}}{g_{XH}}}\left[\frac{g_{COD}}{d}\right] \quad (5)$$

Eq. (6) shows the carbon removal by adsorption (COD_{ads}) resulting from the difference between the measured COD removal and the calculated COD_{bio}

$$COD_{ads} = \left(\left(c_{0,COD} - c_{i,COD}\right)\frac{g_{COD}}{m^3} * Q_i\frac{m^3}{d} - COD_{bio}\right)\left[\frac{g_{COD}}{d}\right] \quad (6)$$

In order to calculate the carbon balance for DOC as well, the DOC to COD ratio in the influent to the filters (SP0) was calculated for each measurement point. On average, the DOC to COD ratio at SP0 was 0.38 mg DOC/mg COD

2.3.2. Calculation of removal and carbon usage rate (CUR)

The relative removal of OMPs, O_2 and nutrients in the GAC filters was calculated in relation to the influent concentration using Eq. (7):

$$\text{Removal} = \frac{c_0 - c_i}{c_0}[-] \quad (7)$$

c_0: Influent concentration to the GAC filters
c_i: Concentration at sampling point i (SP1 to SP4)

The specific removal rate in g/(d*kg_{GAC}) for DOC, NH_4-N, NO_2-N, NO_3-N, TP and O_2 and in mg/(d*kg_{GAC}) for OMPs was calculated by multiplying the removal by the feed rate and dividing by the GAC mass (m_{GAC} = 43.47 kg/filter). In order to assess the removal efficiency of GAC filters regarding OMPs, the following summation parameters are used for the evaluation:

- NRW: All 6 indicator substances on the 2016 NRW list
- $UWWTD_{total}$: All 12 indicator substances listed in the 2024 revised UWWTD
- $UWWTD_{low\text{-}biodegr.}$: All OMPs in the UWWTD that exhibit low or moderate biodegradability in GAC filters
- $UWWTD_{high\text{-}biodegr.}$: All OMPs in the UWWTD that exhibit high biodegradability in GAC filters

To calculate the removal of OMP summation parameters (NRW, $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$, $UWWTD_{high\text{-}biodegr.}$), the removal for the corresponding individual OMPs were first calculated following Eq. (7), and then the average removal of those OMPs was determined as described in the EU UWWTD (European Union 2024). In the EU UWWTD the 12 OMPs are divided into category 1 ("substances that can be very easily treated": amisulpride, citalopram, carbamazepine, clarithromycin, diclofenac, hydrochlorothiazide, metoprolol and venlafaxine) and category 2 ("substances that can be easily disposed of": 1H-benzotriazole, ∑4-/5-methylbenzotriazole, candesartan and irbesartan). The EU UWWTD proposes monitoring the breakdown of OMPs based on six selected substances from the total of 12 listed OMPs ($UWWTD_{6\ out\ of\ 12}$). Four of these selected OMPs may be chosen from category 1 and two from category 2. Moreover, the EU UWWTD sets an elimination target of over 80 % for OMPs, measured on dry weather days. As the main biological treatment stage is already capable of removing some of the OMPs, the balance limit for compliance with the 80% elimination target is set for the entire WWTP (from the effluent of the primary clarifier to the effluent of the GAC filter).

The carbon usage rate (CUR) is applied to compare the BV that are processed until a threshold criterion (80 % removal) is reached with the amount of activated carbon (AC) used. Eq. (8) shows the calculation of the CUR based on Worch (2021):

$$CUR = \frac{V_F * \rho_F}{BV * V_F} = \frac{\rho_F}{BV}\left[\frac{mg_{AC}}{L}\right] \quad (8)$$

V_F: Filter bed volume
ρ_F: Filter bulk density

2.3.3. Statistical calculations

Box plots and a linear mixed-effects model (LMM) were used for the statistical analysis and presentation of the data. The significance of differences in removal or specific removal rates was assessed on the basis of the LMM results. A significance level of $\alpha = 0.05$ was applied. Further information on the implementation of the LMM and the presentation of the box plots can be found in the SI (Chapter 1.5). An overview of all calculated p-values is also provided in the SI.

3. Results and discussion

3.1. Influent DOC removal does not reflect biological activity in the GAC filters

While O_2 consumption exhibits marked seasonal fluctuations with an upward trend as temperatures rise, DOC degradation in the three GAC filters remains at a comparatively constant level throughout the years. In addition, the nutrient balances conducted show that the measured reduction in influent DOC is considerably lower than would be expected based on O_2 and nitrogen consumption. Consequently, the difference between the measured DOC and the DOC calculated from O_2 consumption (DOC_{bio}) is largely negative. The resulting adsorbed DOC (DOC_{ads}) is therefore positive only during the first few months of operation. This means that, only in the first few months, more DOC was removed in the GAC filters than would be expected based on O_2 consumption. The discrepancy between the expected increase in biological activity at high temperatures (represented here by the O_2 consumption) and the largely constant DOC degradation is consistent with observations reported in literature (Emelko et al. 2006, Fundneider et al. 2021b, Huck and Sozanski 2008). Consequently, the removal of influent DOC – unlike O_2 consumption - does not indicate seasonally fluctuating biological activity in GAC filters. Fig. 2 shows the carbon balance over the duration of the experiment in the three GAC filters, based on measurements of O_2, NH_4-N, NO_2-N, NO_3-N and carbon (COD and DOC).

The calculated DOC_{bio} levels are highest in GAC Filter C, with the difference to reference filter A continuing to increase starting in the spring of 2023. The predominantly negative DOC_{ads} values suggest that additional substrate sources, apart from the influent DOC, are being utilized for biological growth in the GAC filters. These may be extracellular polymeric substances (EPS) or carbon compounds that have already been adsorbed (Çeçen and Aktas 2012). Moreover, a limitation of the nutrient balance is that it does not account for other microbial processes, such as the decay of biomass, endogenous respiration, or the recycling of internal carbon compounds. This is also evident from the fact that the carbon balance cannot be closed. Consequently, the results of the balance suggest that the O_2 consumption for direct biomass growth—and thus the biological degradation of DOC from the influent—is overestimated. Thus, it can be assumed that calculated DOC_{ads} also reaches the positive balance range at regular intervals. Such fluctuations between positive and negative DOC_{ads} values would mean that the GAC filters act as substrate buffers for biological activity throughout the year.

Since phosphorus compounds are not taken into account in the ASM, a further nutrient balance was established based on the measured TP concentrations. The equation for the phosphorus-based nutrient balance and its results can be found in Chapter 2 of the SI. Unlike the balance shown in Fig. 2, the phosphorus-based balance at regular intervals reaches the positive range for the calculated DOC_{ads}. However, here too, the carbon balance cannot be fully closed. Overall, the phosphorus-based balance, like the O_2-based balance, shows seasonal fluctuations. Consequently, the TP measurements – unlike the DOC measurements – also show seasonal fluctuations, which could be a further indication of seasonally varying biological activity in the GAC filters. However, it should be noted that TP does not consist solely of bioavailable phosphorus compounds. Thus, conclusions drawn from the phosphorus-based balance regarding biological activity in the GAC filters are also subject to considerable uncertainty.

3.2. The bioavailable substrate load in the influent influences the biological activity in the GAC filters

In line with the inability of influent DOC removal to accurately reflect the biological activity within the GAC filters (see Chapter3.1), the study by Graß et al. (2025) showed that DOC degradation in filter A is limited by the bioavailable DOC fraction in the influent. Moreover, the comparison of the GAC filters with one another reinforces the assumption that the bioavailable substrate in the influent impairs biological

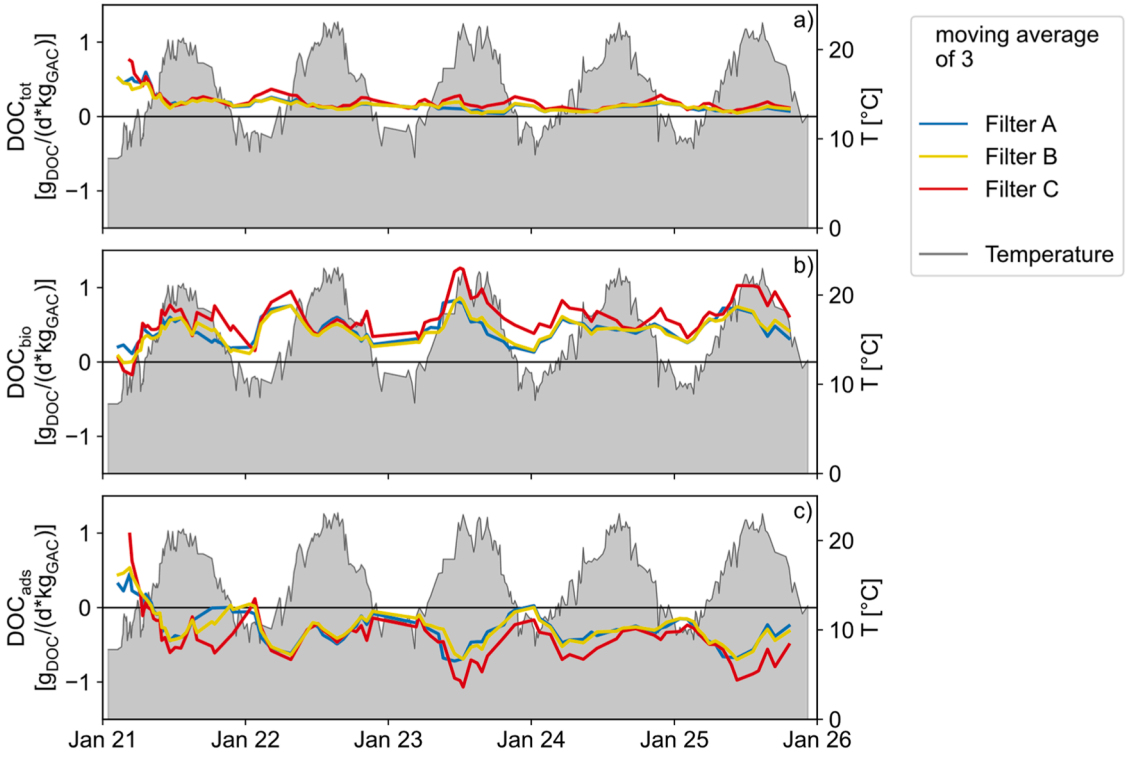


Fig. 2. Carbon balance in the three pilot GAC filters based on O_2, NH_4-N, NO_2-N, NO_3-N and carbon (COD and DOC) measurements. In (a) the measured DOC removal rate (DOC_{tot}), in (b) the biological DOC removal rate (DOC_{bio}) calculated from O_2, NH_4-N, NO_2-N and NO_3-N measurements, and in (c) the adsorptive DOC removal rate (DOC_{ads}) calculated as the difference between DOC_{tot} and DOC_{bio}.

activity in the GAC filter. For comparison of the GAC filters with one another Fig. 3 shows the removal and the specific removal rate of all three GAC filters for the parameters O_2 and DOC.

The higher backwash frequency in filter B did not result in any significant difference in DOC and O_2 removal ($p = 0.722$ respectively $p = 0.338$) or specific removal rates ($p = 0.770$ respectively $p = 0.770$) compared with filter A (considering the entire pp 2). Consequently, backwashing (weekly versus every 2–3 weeks) shows no significant effect on the predominantly biological degradation of O_2 and DOC during the biologically active phase. This therefore further supports the statement that it is the bioavailable substrate in the influent—and not the frequency at which biomass is flushed out of the filter—that limits O_2 and DOC removal in the biologically active GAC filters (pp 2).

The comparison between filter A and filter C also reinforces this observation. By increasing the feed rate by a factor of two, filter C removes significantly ($p < 0.001$) more DOC and O_2 per day than filter A. Thus, increasing the bioavailable DOC load in the influent enhances the specific O_2 removal rate. If biological activity is associated with O_2 consumption, this also implies that biological activity is higher when the substrate loading in the influent is higher. This is only possible as long as the biomass present in the filter is not the limiting factor for biological activity.

However, unlike the absolute removal rates, the relative removal of DOC and O_2 in Filter C is lower than in Filter A. As the data from pp 2 was used in this comparison, filter C differs from filter A not only in terms of EBCT and $v_{filtr.}$ but also, in the number of BV processed. As far as biodegradation is concerned, the higher number of BV introduced is not expected to lead to a deterioration in performance. Consequently, the lower observed relative removal can be attributed either to the lower adsorption capacity of GAC filter C or to the altered hydraulic conditions (lower EBCT and higher v_{filtr}).

3.3. Higher DOC and O_2 removal rates have a positive effect on the degradation of highly bioavailable OMPs

When comparing the three GAC filters, OMP removal exhibits similar patterns to the removal of O_2 and DOC. Fig. 4 shows the removal and specific removal rate of all three GAC filters for the parameters $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{high\text{-}biodegr.}$.

Filter C shows significantly lower relative removal ($p < 0.001$ and $p < 0.001$) and significantly higher specific removal rates ($p = 0.004$ and $p < 0.001$) for both $UWWTD_{low\text{-}biodegr}$ and $UWWTD_{high\text{-}biodegr}$. However, the difference in the specific removal rates between filter A and filter C is most pronounced for $UWWTD_{high\text{-}biodegr.}$.This suggests that the improved absolute removal in filter C is primarily attributable to enhanced biodegradation. In line with this the lower relative removal is more pronounced for $UWWTD_{low\text{-}biodegr}$. This suggests that these OMPs are more severely affected by the drawbacks of filter C (higher number of BV processed / altered hydraulic conditions).

For $UWWTD_{total}$, the relative removal and the specific removal rate in filter B show no significant difference ($p = 0.314$ and $p = 0.231$) from those in filter A, just as is the case with O_2 and DOC. However, in terms of relative removal and specific removal rate of $UWWTD_{high\text{-}biodegr.}$, the performance of filter B is significantly lower ($p < 0.001$ and $p = 0.002$) than that of filter A. Regarding $UWWTD_{low\text{-}biodegr.}$, no significant difference was observed between filter A and filter B in terms of either relative removal ($p = 0.474$) or specific removal rate ($p = 0.437$). Consequently, the longer backwash interval in filter A shows only a positive effect on the removal and the specific removal rate of readily biodegradable OMPs. Overall, the higher flow rate in filter C has a

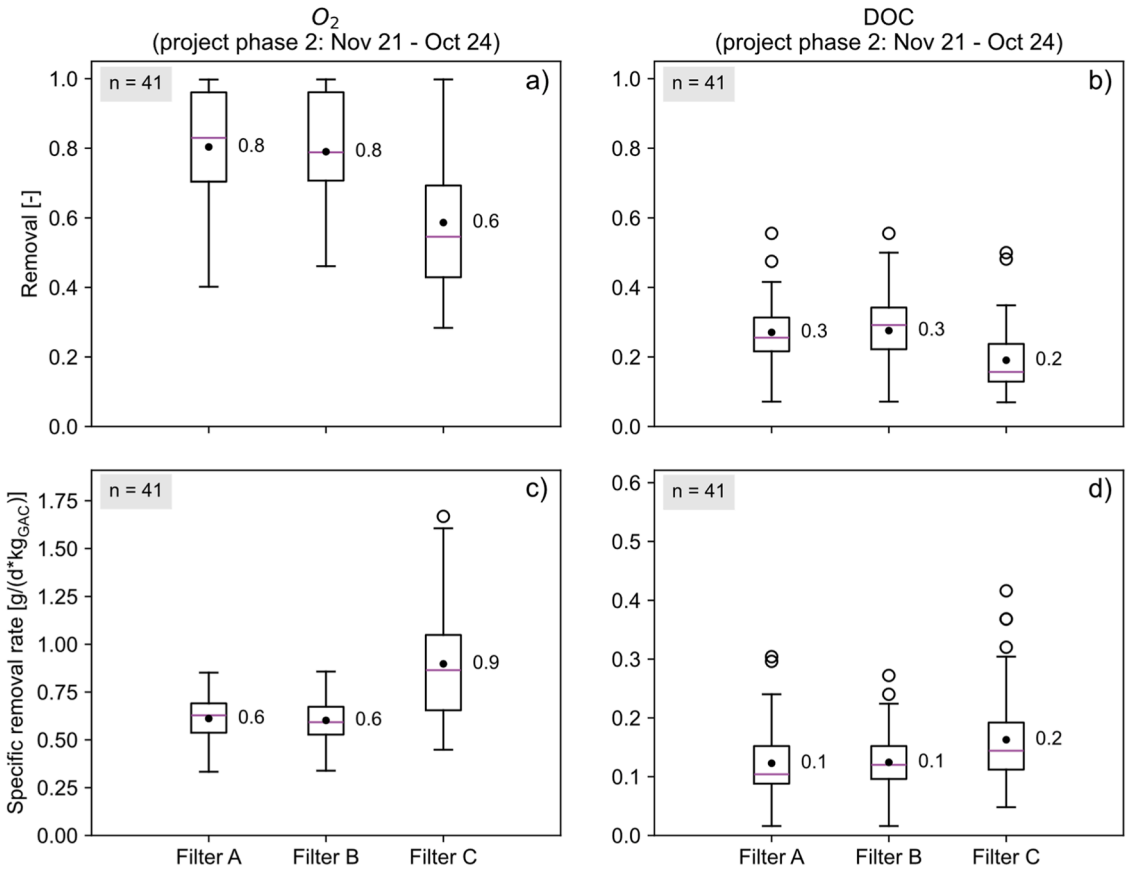


Fig. 3. Removal and specific removal rate of all three GAC filters for the parameters O_2 and DOC in pp 2 (Nov 21 – Oct 24). Sub-figures (a) and (b) show the removal in all three GAC filters for the parameters O_2 and DOC respectively. Sub-figures (c) and (d) show the specific removal rate in all three GAC filters for the parameters O_2 and DOC respectively.

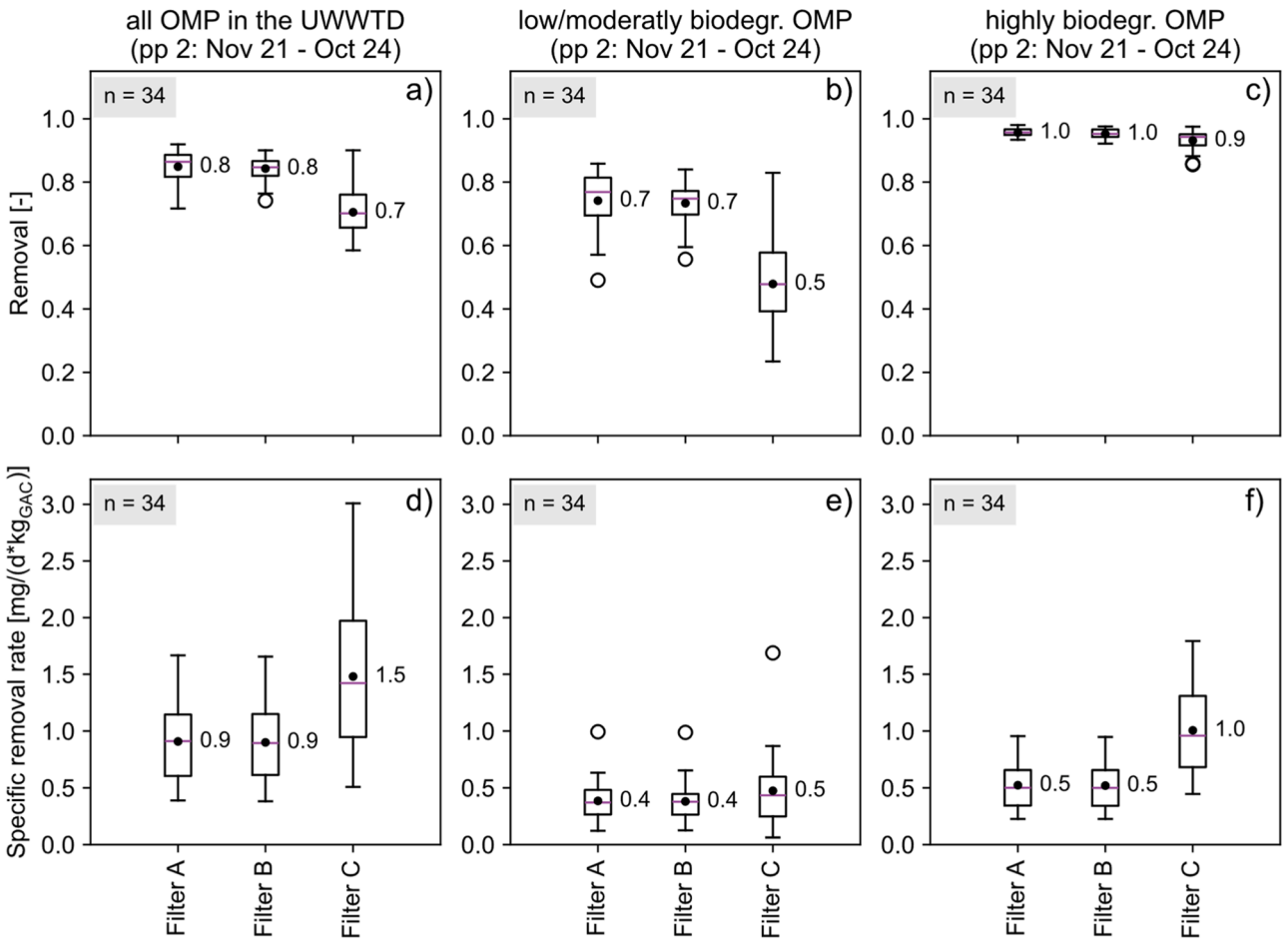


Fig. 4. Removal and removal rate of all three GAC filters for the parameters UWWTD, $UWWTD_{low\text{-}biodgr.}$ and $UWWTD_{high\text{-}biodegr.}$ in pp 2 (Nov 21 – Oct 24). Sub-figures (a), (b) and (c) show the removal in all three GAC filters for the parameters UWWTD, $UWWTD_{low\text{-}biodgr.}$ and $UWWTD_{high\text{-}biodegr}$ respectively. Sub-figures (c), (d) and (g) show the specific removal rate in all three GAC filters for the parameters UWWTD, $UWWTD_{low\text{-}biodgr.}$ and $UWWTD_{high\text{-}biodegr}$ respectively.

greater effect on both the low- and high-biodegradable OMPs than the adjusted backwash frequency in filter B. Consequently, the analysis of the individual OMP groups also suggests that the higher substrate loading in filter C is a key factor for increased removal rates of biologically available compounds. However, contrary to what might be expected from the O_2 and DOC measurements, the bioavailable OMPs also show that backwashing has a significant influence on their removal behaviour.

3.4. *Pretreatment using UF extends GAC filter service life*

When comparing the three GAC filters, filter C falls below the 80% removal target (set by the EU UWWTD) for NRW, $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{high\text{-}biodegr.}$ at considerably lower BV than filter A. Compared with filter B, filter A achieves similar operation times until the 80% removal target is reached. Fig. 6 in the SI shows the removal over the course of the BV in the combination of the WWTP Nette and the pilot plant for NRW, $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{high\text{-}biodegr.}$. For GAC filter C, the 80 % target for $UWWTD_{total}$ and $UWWTD_{low\text{-}biodegr.}$ was already missed for the first time before all relevant OMPs were included in the scope of the analysis. Consequently, the $UWWTD_{total}$ and $UWWTD_{low\text{-}biodegr.}$ in filter C no longer met the 80 % target at < 44,900 BV (CUR > 10.0 mg_{AC}/L). In filter A, however, the 80 % target had still not been missed even at the end of the pilot study for $UWWTD_{total}$ (> 57,900 BV; CUR < 7.8 mg_{AC}/L). The $UWWTD_{low\text{-}biodegr.}$ level in GAC filter A fell below the 80% target for the first time after 30,000 BV (CUR = 15.0 mg_{AC}/L). Regarding $UWWTD_{high\text{-}biodegr.}$, none of the filters tested fell short of the 80% target. Consequently, these OMPs were still sufficiently removed with > 111,900 BV (CUR < 4.0 mg_{AC}/L) in filter C.

The UWWTD proposes selecting 6 out of the 12 indicator substances for the regulatory monitoring of micropollutant removal. When this monitoring method is used ($UWWTD_{6\ out\ of\ 12}$), the 80 % threshold is not breached until the end of the pilot phase, just as is the case with $UWWTD_{high\text{-}biodegr.}$. Table 1 shows the BV reached and the corresponding CUR values that can be attained until the 80 % removal target is missed for various OMP summation parameters and the different GAC filters. In addition, this analysis was carried out for the individual OMPs to examine the impact of biodegradation and adsorption on filter service life.

In Benstoem et al. (2017), the BV to reach the 80 % breakthrough threshold for diclofenac and carbamazepine were compiled from 44 GAC filter studies. For both diclofenac and carbamazepine, only three studies achieved BV greater than 15,000 before reaching the 80 % threshold. Two of these three studies (BV > 15,000) used UF as a pre-treatment. Comparing diclofenac and carbamazepine ("very well/-well" adsorbable), the two substances exhibited similar breakthrough behaviour (Benstoem et al. 2017). In line with Benstoem et al. (2017), Worch (2021) report typical filter service lives for GAC filters ranging from 2,000 to 20,000 BV (100 to 600 operation days).

The SI (Table 5) contains the same analysis as in Table 1, excluding the pretreatment stages (WWTP Nette and UF) of the GAC filters. The achievable operating times until the 80 % threshold is reached, without taking the pre-treatment stages into account, show similar results for

Table 1
BV reached and the corresponding CUR values that can be attained until the 80 % removal target is missed for various OMP summation parameters/individual OMPs and the different GAC filters. Only days with dry weather were included in this analysis. The removal was calculated between the effluent of the primary clarifier and the effluents of the 3 GAC filters. The individual OMPs are classified according to their biodegradability in the GAC filters. OMPs with poor biodegradability are shown in red. OMPs with moderate biodegradability are shown in yellow. OMPs with good biodegradability are shown in green. Within each class, the OMPs are sorted in ascending order according to their kf values (see SI Table 3).

	Filter A		Filter B		Filter C	
	BV [-]	CUR [mg_{AC}/L]	BV [-]	CUR [mg_{AC}/L]	BV [-]	CUR [mg_{AC}/L]
NRW	49,300	9.1	49,100	9.2	27,700	16.2
$UWWTD_{total}$	> 57,100	< 7.9	> 57,900	< 7.8	< 44,900	> 10.0
$UWWTD_{low\text{-}biodegr}$	30,000	15.0	26,900	16.7	< 44,900	> 10.0
$UWWTD_{high\text{-}biodegr}$	> 57,100	< 7.9	> 57,900	< 7.8	>110,800	< 4.1
$UWWTD_{6\ out\ of\ 12}$	> 57,100	< 7.9	> 57,900	< 7.8	>110,800	< 4.1
carbamazepine	24,500	18.4	24,700	18.2	27,700	16.2
candesartan	< 23,000	> 19.6	< 23,700	>19.0	< 44,900	> 10.0
1H-benzotriazole	29,000	15.5	29,700	15.1	47,929	9.4
irbesartan	48,300	9.3	49,100	9.2	< 44,900	> 10.0
venlafaxine	> 57,100	< 7.9	> 57,900	< 7.8	< 44,900	> 10.0
∑4-/5-methylbenzotriazole	26,100	17.2	26,900	16.7	47,929	9.4
citalopram	> 57,100	< 7.9	> 57,900	< 7.8	> 110,800	< 4.1
amisulpride	> 57,100	< 7.9	> 57,900	< 7.8	> 110,800	< 4.1
clarithromycin	> 57,100	< 7.9	> 57,900	< 7.8	44,900	10.0
diclofenac	> 57,100	< 7.9	> 57,900	< 7.8	>110,800	< 4.1
hydrochlorothiazide	> 57,100	< 7.9	> 57,900	< 7.8	> 110,800	< 4.1
metoprolol	> 57,100	< 7.9	> 57,900	< 7.8	> 110,800	< 4.1

filters A and B to those in Table 1. For filter C the achievable filter service life of 18,700 BV for carbamazepine and 22,800 BV for diclofenac are substantially lower than when the pretreatment stages are considered (27,700 BV respectively >111,900 BV). However, even without taking pretreatment into account, the GAC filter service life distinctly exceed the 15,000 BV reported in Benstoem et al. (2017).

Although elevated feed concentrations of particulate matter result in increased backwash frequencies, no reliable evidence was found in Benstoem et al. (2017) regarding the influence of pretreatment (suspended solids removal) on adsorptive OMP removal in GAC filters. However, the results of Baresel et al. (2024) and Takman et al. (2023) show that decisively longer GAC filter service life can be achieved in a process combination of membrane bioreactors (MBR) and GAC filtration. For the $UWWTD_{6\ out\ of\ 12}$, GAC filter service life in Baresel et al. (2024) exceeded 50,000 BV (2-stage filters; $EBCT_{each}$: 10 min: v_{filtr}: 10 m/h). Takman et al. (2023) reported a resurgence in OMP removal performance in the GAC filters at approximately 15,000 BV in the process combination of MBR and GAC. Moreover, Larasati et al. (2026) demonstrated that even after more than 400,000 BV, biologically active GAC (EBCT: 15-30 min; v_{filtr}: 5-10 m/h), following pretreatment by UF, is capable of degrading a wide range of OMPs by more than 80%. Our findings and the evidence from literature therefore suggest that the achieved BV reported in Benstoem et al. (2017) do not reflect biologically active GAC filters, or rather that they relate primarily to the adsorption phase of GAC filters. This is also evident in the removal behaviour of diclofenac and carbamazepine. Unlike in the CAS, diclofenac exhibits high biodegradability in biologically active GAC filters. Carbamazepine, on the other hand, remains biologically persistent (Baresel et al. 2019, Graß et al. 2026, Takman et al. 2023). The high removal of diclofenac even at high BV therefore suggests a high rate of biodegradation (Baresel et al. 2019, Karakurt-Fischer et al. 2026). In the case of carbamazepine, however, there are indications that the improved removal in biologically active GAC filters points to biological regeneration of the GAC (Baresel et al. 2019, Takman et al. 2023). Overall, the data in Table 1 show that, with one exception, all readily biodegradable OMPs remained above the 80 % removal target by the end of the test period. Furthermore, OMPs with low to moderate biodegradability have mostly exceeded 20,000 BV before they were no longer able to meet the 80 % target. We therefore hypothesise that UF pretreatment has a beneficial effect on the development of biological activity within the GAC filters, which can compensate for the decline in adsorption capacity. However, as this study does not include a reference filter operated without UF pre-treatment, this question cannot be conclusively resolved. Furthermore, it is possible that other processes, such as deep-bed filtration or cloth-filtration, may have the same effect as UF as a pre-treatment stage. In addition to removing particulate matter, these processes may also affect the bioavailable substrate in the influent to the GAC filters. The results of this study suggest that both of these factors may influence the biological activity within the GAC filters.

3.5. *Hydraulic conditions can hinder the exploitation of the biodegradation capacity in GAC filters*

Filter C falls below the 80 % removal target at considerably lower BV than filter A. In the following, the differences in the hydraulic conditions between filter A and filter C are examined. Unlike v_{filtr}, the EBCT was identified in literature as a key process parameter for the design of GAC filters. It determines the retention of OMPs within the GAC granules and the contact time between the OMPs and the active biomass (Fundneider et al. 2021a, Larasati et al. 2026). To investigate the impact of v_{filtr} independently of EBCT, the intermediate sampling points SP1 in filter A and SP3 in filter C were compared with one another. As shown in Fig. 3 in the SI, the flow profiles of these two sampling points, with EBCT of 17 and 16 min respectively, run largely parallel. The v_{filtr} in filter A is 3.15 m/h and in filter C 6.3 m/h. In pp 4, v_{filtr} of filter C was reduced to 4.2 m/h. Fig. 5 shows the difference in relative removal between filter A (SP1) and filter C (SP3) for the OMP summation parameters NRW, $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{high\text{-}biodegr.}$.

For all OMP summation parameters, a significantly higher OMP removal was observed in filter A (SP1) compared with filter C (SP3) in pp 2 and 3 across all years studied. The difference between the sampling points examined is greater for $UWWTD_{low\text{-}biodegr.}$ than for $UWWTD_{high\text{-}biodegr.}$. Consequently, the removal of readily biodegradable substances is less severely impaired by the higher v_{filtr} in filter C than that of poorly biodegradable substances. Moreover, the results indicate that biological activity might have a beneficial effect on OMP removal. This is reflected by the downward trend in the summation parameter NRW in Fig. 5 over time. Whilst the difference of DOC_{bio} between filters A and C increases over time (see Fig. 2), the negative impact of higher v_{filtr} in filter C decreases. Thus, higher biological activity might have the potential to counteract the adverse transport conditions (higher v_{filtr}) in the case of highly biodegradable OMPs.

In pp 4, there is no longer any significant difference in the removal between the two sampling points for NRW ($p = 0.114$). However, due to

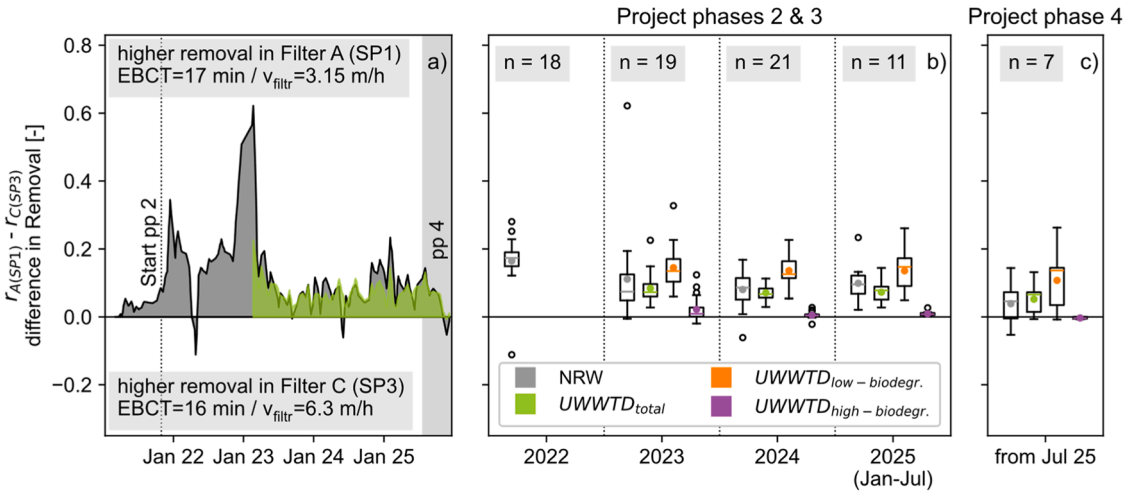


Fig. 5. Difference in relative removal between sampling points Filter A (SP1) and Filter C (SP3) plotted against filter service life for the summation parameters NRW and $UWWTD_{total}$ in (a). In (b), the parameters NRW, $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{high\text{-}biodegr.}$ are shown in pp 2 and 3, broken down by year. In (c), the difference in relative removal is shown for the same parameters as in (b) for pp 4.

the reduction in v_{filtr} (from 6.3 to 4.2 m/h), the EBCT in filter C (SP3) has also increased to 24 min. Consequently, it is unclear in pp 4 whether the effect can be attributed to the different EBCT and/or v_{filtr}. Unlike in this study, Fundneider et al. (2021a) found that there was no further increase in removal efficiency between v_{filtr} values of 9.3 and 3.7 m/h and corresponding EBCT of 25 to 33 min. This could suggest that, particularly at lower EBCT (< 20 min), v_{filtr} has a greater influence on OMP removal. All in all, our results show that it is the hydraulic parameters (EBCT and v_{filtr}) which might hinder the exploitation of the biological activity in the GAC filters and thus their OMP removal performance. This is consistent with the findings of Karakurt-Fischer et al. (2026), who discovered that an increased contact time (CT) is particularly beneficial for exploiting biological OMP degradation processes. In the experimental setup used by Karakurt-Fischer et al. (2026), EBCT of up to 100 min were examined for the biologically active GAC filters. Larasati et al. (2026) also concluded that EBCT greater than 26 min are necessary to make sufficient use of the biological degradation of OMPs in GAC filters. Consequently, other literature sources point out that the observation whereby EBCT greater than 25–30 min has no further effect on OMP removal in GAC filters (Fundneider et al. 2021a) applies to filters that operate predominantly by adsorption. When comparing Filter A (EBCT = 40 min) and Filter C (EBCT = 20 min), Filter A shows improved OMP degradation in the biologically active state, which neither refutes nor confirms the above statement.

3.6. *The impact of backwash frequencies decreases with increasing filter service life*

The hypothesised effect of UF pretreatment (Chapter 3.4) suggests that the concentration of suspended solids in the influent, and consequently the backwash frequency, influences OMP removal performance of GAC filters. However, when considering the total pp 2, there is no significant difference between filter A and filter B in terms of DOC and O_2 removal, or in the removal of $UWWTD_{total}$.. Consequently, a more detailed analysis with a higher temporal resolution was carried out to further examine the impact of higher backwash frequencies on OMP removal. Fig. 6 shows the difference in relative OMP removal between filter A and filter B over the entire project duration, broken down into time intervals.

In pp 1, prior to the first backwash, the OMP removal performance

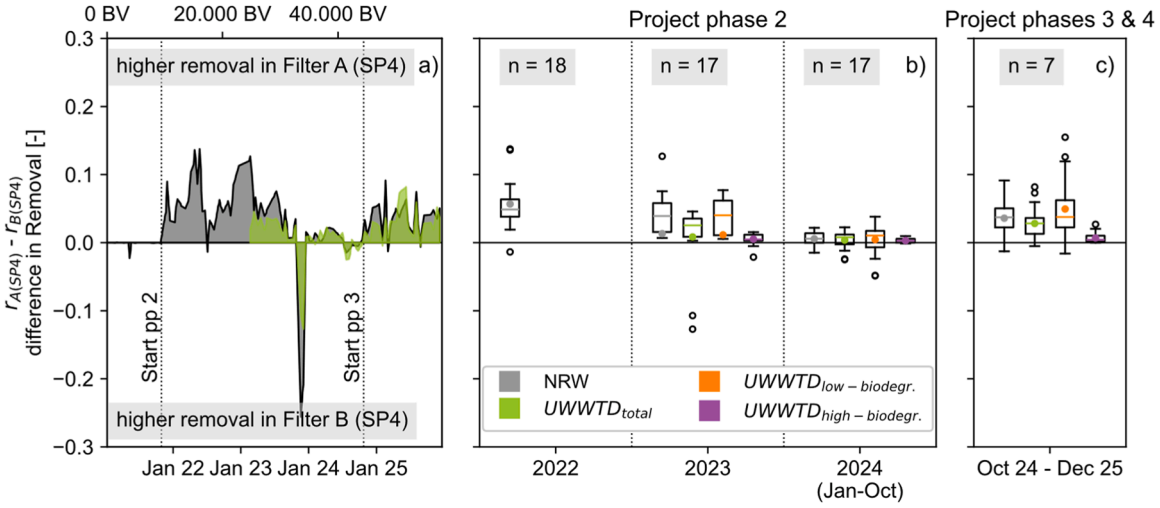


Fig. 6. Difference in relative removal between filter A and filter B plotted against filter service life for the summation parameters NRW and $UWWTD_{total}$ in (a). In (b), the parameters NRW, $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{high\text{-}biodegr.}$ are shown in pp 2, broken down by year. In (c), the difference in relative removal is shown for the same parameters as in (b) for pp 3 and 4.

(NRW) is almost identical in both filters. Once regular backwashing begins, an improvement in removal can be observed in filter A over filter B. However, the difference between filter A, which is backwashed every 2 to 3 weeks, and filter B, which is backwashed weekly, continues to decrease over the course of pp 2. It is only from pp 3 onwards, when the backwashing frequency in filter B was increased to daily, that the difference between the two filters rises again in favour of filter A. The effect of an increased backwash frequency therefore decreases as the BV increase. For example, a daily backwash interval has a smaller effect on OMP removal (NRW) in pp 3 and 4 than a weekly interval at the start of pp 2.

When the period covered by pp 2 is broken down into individual years, the removal in $UWWTD_{total}$ and $UWWTD_{low\text{-}biodegr.}$ shows no significant difference between filter A and filter B (2023: $p = 0.337$ and $p = 0.436$; 2024: $p = 0.245$ and $p = 0.460$). On the other hand, the summation parameters NRW (2022: $p < 0.001$; 2024: $p = 0.03$) and $UWWTD_{high\text{-}biodegr.}$ (2023: $p = 0.007$; 2024: $p < 0.001$) show a significant difference in removal between filter A and filter B. In pp 3 and 4, the difference in removal is significant for all four OMP summation parameters ($p < 0.001$).

The results show that the effect of backwashing depends on the filter BV examined. Furthermore, the variations in backwash frequencies examined consistently show a significant influence on the removal of highly biodegradable OMPs. This suggests that it is primarily the biodegradation processes that are impaired by backwashing. This is consistent with the findings of Fundneider (2020), who identified backwashing as an operating parameter for biomass regulation in GAC filters with a free-of-solids feed. The diminishing influence of backwash frequency throughout filter service life also suggests that, once sufficient biomass has built up in the GAC filters, differences in specific backwash frequencies are no longer a decisive factor. This is apparent, for example, from 30,000 to 35,000 BV and onwards, where a weekly backwash interval, compared with a two- to three-weekly interval, no longer shows a significant difference in the removal of $UWWTD_{total}$. However, the main difference compared to purely adsorptive GAC filters is not the backwash frequency whilst the system is biologically active, but rather that the GAC filters were not backwashed at all up to approximately 10,000 BV. Consequently, the effect of a higher backwash frequency might not directly be apparent in the OMP removal of purely adsorptive GAC filters (Benstoem et al. 2017), but might become evident in the long term through the development of biological activity. This is also evident in the study by Takman et al. (2023), who observed an increase in biological activity at approximately 15,000 BV. In the study by Takman et al. (2023), the GAC filters (fed on a flow-dependent basis with an average EBCT = 51 min) were backwashed for the first time after 46 weeks of operation. As in this study, the GAC filters were pre-treated using an MBR. Consequently, literature sources and our data show that the filters should not be backwashed during the first 10,000–15,000 BV in order to achieve filter service lives of >> 15,000 BV.

3.7. *Higher temperatures promote the degradation of highly bioavailable OMPs in the upper filter layers*

The comparison of the three GAC filters with one another and the

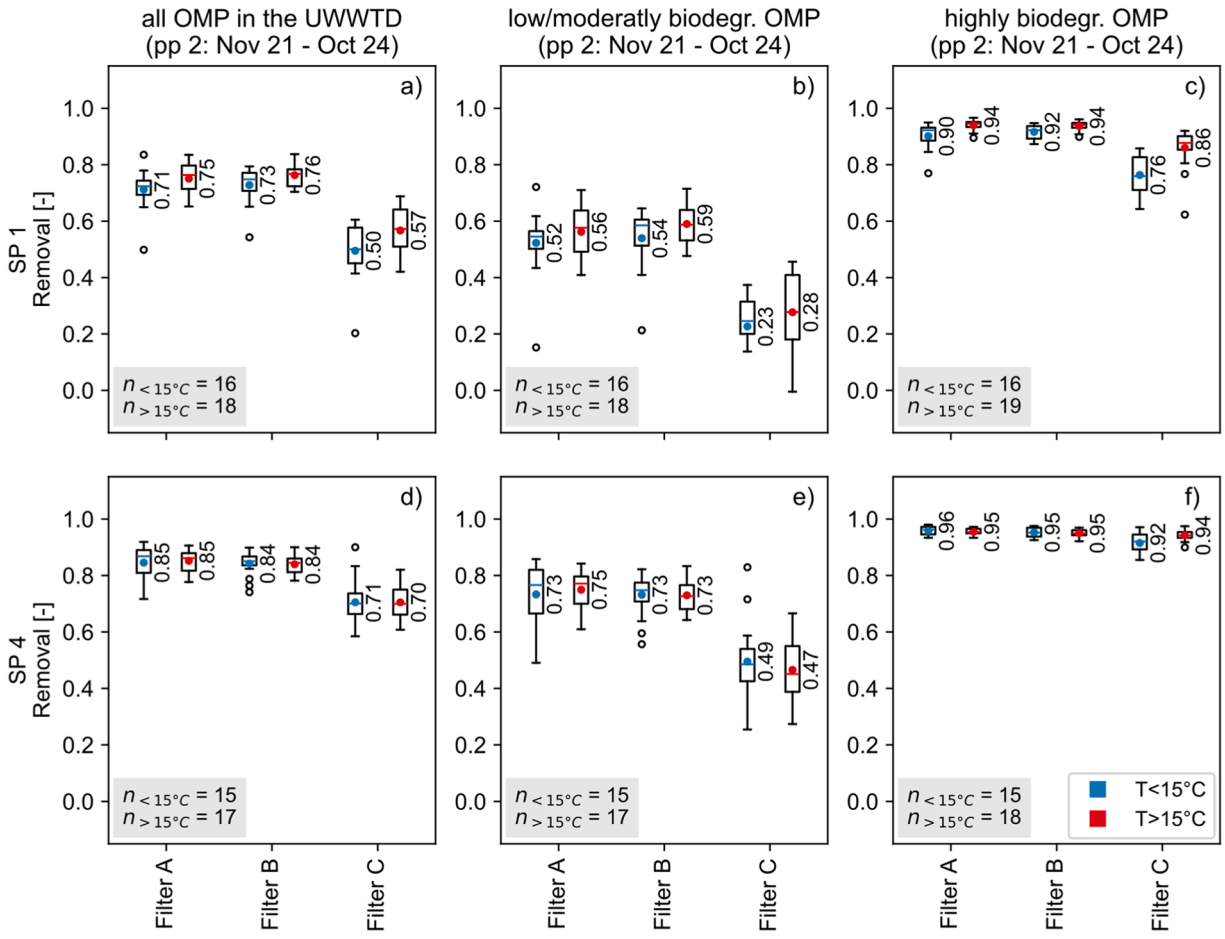


Fig. 7. Removal of $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{highly\text{-}biodegr.}$ in the three GAC filters, broken down into measurements taken at temperatures below and above 15°C. The evaluation period covers pp 2. The analysis was carried out on both SP1 (shown in sub-figures (a), (b) and (c)) and SP4 (shown in sub-figures (d), (e) and (f)) of all three GAC filters.

analysis of the effects of various process parameters indicate that higher biological activity leads to improved OMP removal. Another external parameter that may provide insights into the effects of increased biological activity on OMP degradation is temperature. Graß et al. (2026) showed that, in addition to biological activity, the adsorption of individual OMPs is also strongly influenced by temperature. Consequently, it cannot generally be assumed that higher temperatures lead to improved OMP removal in GAC filters. Fig. 7 shows the removal of $UWWTD_{total}$, $UWWTD_{low\text{-}biodegr.}$ and $UWWTD_{highly\text{-}biodegr.}$ in SP1 and SP4 of all three GAC filters, broken down into measurements taken at temperatures below and above 15°C. As the temperature differences were due to seasonal variations, the comparison in Fig. 7 does not involve corresponding samples. Consequently, the proportionately high influence of other external factors must be considered when interpreting the results.

Among all three GAC filters and summation parameters examined, in SP4 only the removal of $UWWTD_{high\text{-}biodegr.}$ in filter C is significantly higher at temperatures above 15°C compared with those below 15°C. Unlike filters A and B, filter C exhibits greater seasonal fluctuations in OMP removal performance when in the biologically active state. Furthermore, the overall OMP removal performance in the biologically active state of filter C is lower than in the other two GAC filters (Chapter 3 in the SI). Consequently, the higher EBCT in filters A and B leads to improved removal of highly biodegradable OMPs (mostly below the LOQ) at both high and low temperatures. This is consistent with the findings of Larasati et al. (2026), who recommended an increase in EBCT at lower temperatures for biologically active GAC filters. This is also confirmed by the analysis at SP1. At this filter bed depth, $UWWTD_{highly\text{-}biodegr.}$ shows significantly higher removal at temperatures above 15°C compared with temperatures below 15°C in all three GAC filters (filter A: $p = 0.001$; filter B: $p = 0.005$; filter C: $p < 0.001$). Consequently, the reduction of the EBCT in filters A and B to 17 min also results in significant temperature-related differences in the degradation performance of biodegradable OMPs. However, the differences in $UWWTD_{low\text{-}biodegr.}$ remain insignificant in SP1 (filter A: $p = 0.236$; filter B: $p = 0.090$; filter C: $p = 0.250$). As the adsorptive degradation of OMPs can be affected both negatively and positively by higher temperatures (Graß et al. 2026), the temperature-related fluctuations of OMPs can partially counterbalance each other. However, the temperature-dependent differences in the degradation of $UWWTD_{highly\text{-}biodegr.}$ further indicate that biological activity is subject to seasonal fluctuations, as previously observed in O_2 removal performance. Nevertheless, due to the exothermic adsorption behaviour of certain poorly biodegradable OMPs (1H-benzotriazole, $\sum$4-5-methylbenzotriazole), the positive effect of higher biological activity at higher temperatures is not immediately apparent in $UWWTD_{total}$ (Graß et al. 2026). Furthermore, it is shown that low EBCT (< 20 min) can limit the exploitation of the biodegradation capacity within the examined temperature range. Consequently, the investigation of the influence of temperature on OMP degradation confirms that the hydraulic components (EBCT, v_{filtr}) are crucial for harnessing the existing biological activity. It is therefore the interplay of suitable conditions for biomass build-up (pre-treatment, backwash frequency) and a sufficient EBCT for the biodegradation rate (temperature-dependent) that ensures the long-term degradation of highly bioavailable OMPs in GAC filters.

4. Conclusions

The results of this study show that biological activation significantly extends the service life of GAC filters. Pretreatment using UF plays a crucial role in compensating for the decline in adsorption capacity early on and to a sufficient extent. Consequently, the suspended solids free feed ensures that the biofilm's induction and growth phases are not disrupted by increased backwashing. Furthermore, suitable hydraulic conditions (EBCT and v_{filtr}) are essential to bridge the gap between declining adsorption capacity and increasing biological activity at approximately 10,000 to 15,000 BV. The detailed conclusions are:

- The average removal of highly biodegradable OMPs ($UWWTD_{highly\text{-}biodegr.}$) remains consistently high (> 90 %) in biologically active GAC filters, even at >115,000 BV (EBCT = 20 min). This also applies to $UWWTD_{6\ out\ of\ 12}$, meaning that, depending on regulatory requirements, CUR values of < 4.0 mg_{AC}/L can be reached.
- In addition to the long-term removal of highly biodegradable OMPs, poorly biodegradable OMPs (e.g. carbamazepine) exhibit prolonged filter service life (>24.000 BV) until their concentration falls below the 80% removal threshold. This could be an indicator of potential bioregeneration of the GAC in the biologically active filters.
- The impact of backwash frequency on OMP removal decreases as the filter service life increases. During the plateau phase of biomass development, it is the bioavailable substrate in the influent, rather than backwashing, that limits biological activity in the GAC filters.
- In addition to EBCT (17/16 min), it is v_{filtr} (3.15/6.3 m/h) that limits the exploitation of existing biological activity with regard to OMP degradation. Moreover, an EBCT of 40 min, compared to 20 min, ensures a longer filter service life until the 80% removal threshold is reached, for both highly biodegradable (e.g. diclofenac) and poorly biodegradable (e.g. carbamazepine) OMPs.
- Unlike DOC removal, O_2 consumption and the removal of readily biodegradable OMPs indicate seasonal/temperature-dependent fluctuations in biological activity in GAC filters

CRediT authorship contribution statement

Larissa Graß: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Hillebrandt:** Resources, Data curation. **Julian Firk:** Resources, Data curation. **Laurence Palmowski:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Benedikt M. Aumeier:** Methodology, Conceptualization. **Thomas Wintgens:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.wroa.2026.100616.

Data availability

Data will be made available on request.

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