Water Reuse

Water Reuse Vol 00 No 0, 1 doi: 10.2166/wrd.2024.009

MBR and GAC filtration followed by UV disinfection – implications for wastewater reuse at full scale

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ABSTRACT

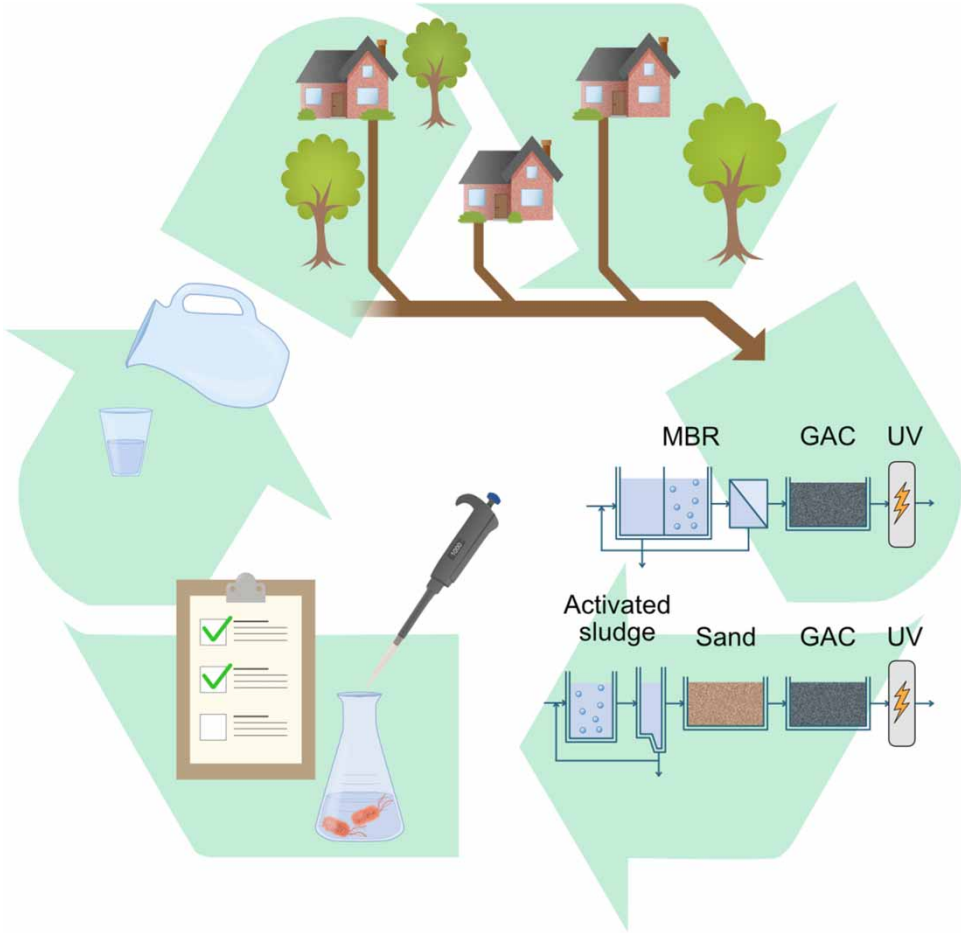
Influences of upstream wastewater treatment on the process combination of granular activated carbon (GAC) and ultraviolet (UV) disinfection were studied and the implications of this for wastewater reuse were assessed. GAC is an efficient chemical barrier but contributes little to the removal of indicator bacteria, and generally increases total bacteria concentrations, necessitating disinfection with UV radiation, for example, to ensure the safe reuse of wastewater. The efficiency of UV disinfection is impacted by factors such as particle concentration and UV absorbance of the water and is thus affected by upstream treatment processes. A full-scale wastewater treatment plant with a membrane bioreactor (MBR) followed by GAC filtration was compared to a treatment plant with a conventional activated sludge process and sand filtration, followed by GAC filtration. The removal of indicator bacteria was higher by the GAC filter that was preceded by an MBR. A UV fluence of 400 J/m^2 was sufficient to reach irrigation water quality for both process combinations and to meet the criteria for microbial drinking water quality in the MBR + GAC effluent. One sample was selected for chemical analysis, comprising approximately 100 parameters, demonstrating that the MBR + GAC + UV (400 J/m^2) effluent met all drinking water criteria except for nitrate levels.

Key words: bacteria, fungi, granular activated carbon, membrane bioreactor, water reclamation

HIGHLIGHTS

- Reuse of wastewater from the full-scale GAC process with subsequent ultraviolet (UV) disinfection.
- Removal of indicator bacteria and fungi by GAC filters.
- Higher removal of microbial contaminants by a GAC filter downstream membrane bioreactor (MBR) versus CAS + sand filtration.
- Chemical and microbial drinking water criteria were met for effluent from MBR + GAC + UV.
- UV fluence of 400 J/m^2 on MBR + GAC effluent sufficient to meet drinking water criteria.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Shifting precipitation patterns due to climate change, combined with population growth and urbanization, have increased water stress and the need for alternatives to dwindling freshwater resources (Ungureanu *et al.* 2020). Parallel with the implementation of wastewater treatment aimed to remove organic micropollutants, for example in Sweden, these trends have generated recent interest in wastewater reuse also in areas where it has not previously been common practice (Takman *et al.* 2023).

Recycled wastewater has several potential uses including agricultural irrigation (Ofori *et al.* 2021) and direct or indirect drinking water production (Drewes & Horstmeyer 2016). Irrigation and potable reuse can reduce the demands on limited surface water and groundwater resources, and irrigation with reused water has potentially positive effects on soil and plants, due to its nutrient content (Vergine *et al.* 2017). Yet, domestic wastewater reuse can pose risks from chemical pollutants, such as organic micropollutants (Fatta-Kassinos *et al.* 2011; Verlicchi *et al.* 2023) or salts (Muyen *et al.* 2011) and pathogens, including bacteria, parasites, and viruses (Jaramillo & Restrepo 2017).

One option for removing organic micropollutants and other chemical contaminants from water is granular activated carbon (GAC) filtration (Frank *et al.* 2015). Full-scale GAC filters for the removal of organic micropollutants from wastewater have been implemented in, for example, Sweden (Takman *et al.* 2023; Svahn & Borg 2024) and Germany (Neef *et al.* 2022) and can be applied for the purpose of wastewater reuse (Reungoat *et al.* 2010; Nahrstedt *et al.* 2020; Hogard *et al.* 2021). In addition to adsorbing chemical pollutants, GAC filters can alter the microbial water quality due to biofilm growth on the granules (Weber *et al.* 1978; Gibert *et al.* 2013; Kantor *et al.* 2019) and increase effluent bacteria concentrations (Wilcox *et al.* 1983; Miller *et al.* 2020).

GAC filters generally do not remove microbial contaminants (Drewes & Horstmeyer 2016), but a small decrease in the concentrations of certain indicator bacteria has been observed after GAC filtration (El-Zanfaly *et al.* 1998; Hijnen *et al.* 2010; Spit *et al.* 2022). The additional removal of pathogens requires different disinfection processes, for example, ozonation (Facile *et al.* 2000; Xu *et al.* 2002), chlorination (Sun *et al.* 2009), or use of ultraviolet (UV) radiation (Hassen *et al.* 2000; Liberti *et al.* 2003). Compared with chlorination and ozonation, UV radiation does not generate any harmful disinfection byproducts, nor does it, as chlorination, result in a residual disinfection that could prevent regrowth in the distribution system (Wang *et al.* 2021).

The disinfection effect from UV treatment varies between microorganisms. A high log removal of the indicator bacteria *Escherichia coli* and other coliform bacteria can in general be achieved (Sommer *et al.* 2000; Mezzanotte *et al.* 2007), whereas higher UV fluences are required to attain the same removal of *Clostridium perfringens* (Hijnen *et al.* 2006; Carabias *et al.* 2023) and yeast (Spotte & Buck 1981). Enterococci can be inactivated to the same extent as *E. coli* and other fecal coliforms (Jacangelo *et al.* 2003), but lower inactivation has also been reported (Locas *et al.* 2008). Further, UV radiation can inactivate pathogens that can be persistent in chlorination (Hijnen *et al.* 2006). It is important to note, however, that UV does not necessarily remove the entire microbial population, but can shift the type of bacteria present in the community (Pullerits *et al.* 2020).

UV radiation damages the DNA of the microorganisms – an effect that is influenced by the absorbance of the solution being exposed, and thus by the suspended solids content of the water (Qualls *et al.* 1983; Carré *et al.* 2018). This means that the effectiveness of the UV treatment is dependent on the upstream treatment processes and the extent to which they remove color and suspended solids (Venditto *et al.* 2022). The combination of GAC and UV is an interesting approach for treating wastewater for reuse (Ponce-Robles *et al.* 2020), since it comprises both a chemical and a microbial barrier, but does not generate potentially toxic disinfection byproducts. Further, unlike reverse osmosis, which is also frequently applied for wastewater reuse, this combination does not result in a concentrate that can be costly to handle (Kehrein *et al.* 2021).

In the Scania region in southern Sweden, there are currently two wastewater treatment plants (WWTPs) that are equipped with GAC filtration, with disparate upstream wastewater treatments: S:t Olof WWTP with a conventional activated sludge (CAS) process and subsequent sand filtration, and Kivik WWTP with an membrane bioreactor (MBR). Both processes are common for wastewater treatment, but result in considerable differences in the effluent water quality, especially regarding particles and bacteria (Drewes & Horstmeyer 2016), potentially affecting the downstream GAC treatment. The biofilm development in full-scale GAC filters continues for long time periods after commissioning of the filters (Takman *et al.* 2023), necessitating full-scale studies of GAC filters with mature biofilm to examine their effects on the microbial water quality.

UV disinfection is planned for incorporation downstream of the MBR + GAC process in Kivik, with its commissioning expected in 2024, and the treated water is planned to be reused for irrigation of, for example, recreational spaces. The effluent from Kivik WWTP is currently of a high chemical and microbial water quality, that in many ways is similar to that of source waters used for drinking water production (Takman *et al.* 2023). The aim of this study was to expand on our knowledge of and experience with these treatment processes, by comparing the effects of UV disinfection of the S:t Olof and Kivik GAC filter effluents, and assessing the potential of the treated effluents for reuse for irrigation or drinking water production.

2. METHODS

Microbial water quality through two different full-scale wastewater treatment processes that include GAC filtration was examined and UV disinfection of these effluents was performed in laboratory experiments. Samples were collected on three occasions (June 12 and 26, and October 2, 2023). Based on the results of the UV experiments and microbial analysis, one sample was selected for extensive chemical analysis of over 100 parameters in the Swedish drinking water criteria (LIVSFS 2022:12).

2.1. Full-scale treatment plants

The MBR and GAC process at Kivik WWTP, dimensioned for 7,500 population equivalents, was commissioned at the end of 2020, and S:t Olof WWTP, dimensioned for 1,000 population equivalents, was equipped with GAC at the start of 2021. Both towns are located in an agricultural landscape in southeast Sweden, and experience a population increase each year between June and August due to tourism and a high number of vacation homes. Kivik WWTP consists of an MBR that is operated for removal of biochemical oxygen demand and is designed with an option for denitrification and nitrification, followed by ultrafiltration (UF) (two membrane units, pore size 0.038 μm, membrane area 9,216 m^2/unit). Downstream of the MBR, the water

passes through two parallel GAC filters with a filter volume of 18 m^3/filter, and an empty bed contact time (EBCT) of 80 min. S:t Olof WWTP comprises a CAS process without the option for nitrogen removal, followed by sand filtration (filter volume 6.4 m^3/filter, EBCT 170 min) and GAC filtration (filter volume 6.4 m^3/filter, EBCT 170 min) (Figure 1). The GAC filters at Kivik WWTP were backwashed approximately once per month, while the GAC filters at S:t Olof WWTP were backwashed approximately twice per year. Technical specifications for the processes are summarized in Table S1.

2.2. UV disinfection

UV disinfection was conducted at the laboratory scale on effluent samples from both WWTPs within three days after sampling. Three UV fluences (approximately 200, 400, and 700 J/m^2; Table 1) were tested using an Aquada 1 UV reactor (Wedeco GmbH, Herford, Germany, length 470 mm and diameter 70 mm) with a monochromatic, low-pressure mercury lamp that emits UV radiation at 254 nm. The range in UV fluences was selected because 400 J/m^2 is a conventional UV fluence at Swedish drinking water treatment plants (Saguti *et al.* 2022).

The UV reactor was placed vertically on a wall with upward water flow and wastewater was pumped through the cylinder containing the UV lamp using a garden pump (MEEC Tools, 800 W, 53.3 L/min) (Figure 2). The pump was connected to a plastic bucket (20 L) that contained the wastewater. The UV fluence was set by adjusting the flow with a valve. The UV lamp had been used in one previous study (Saguti *et al.* 2022). UV irradiance was monitored by a UV sensor that was factory-calibrated to send an alert if the irradiance fell below 70% of the maximum capacity, which did not occur during the experiments.

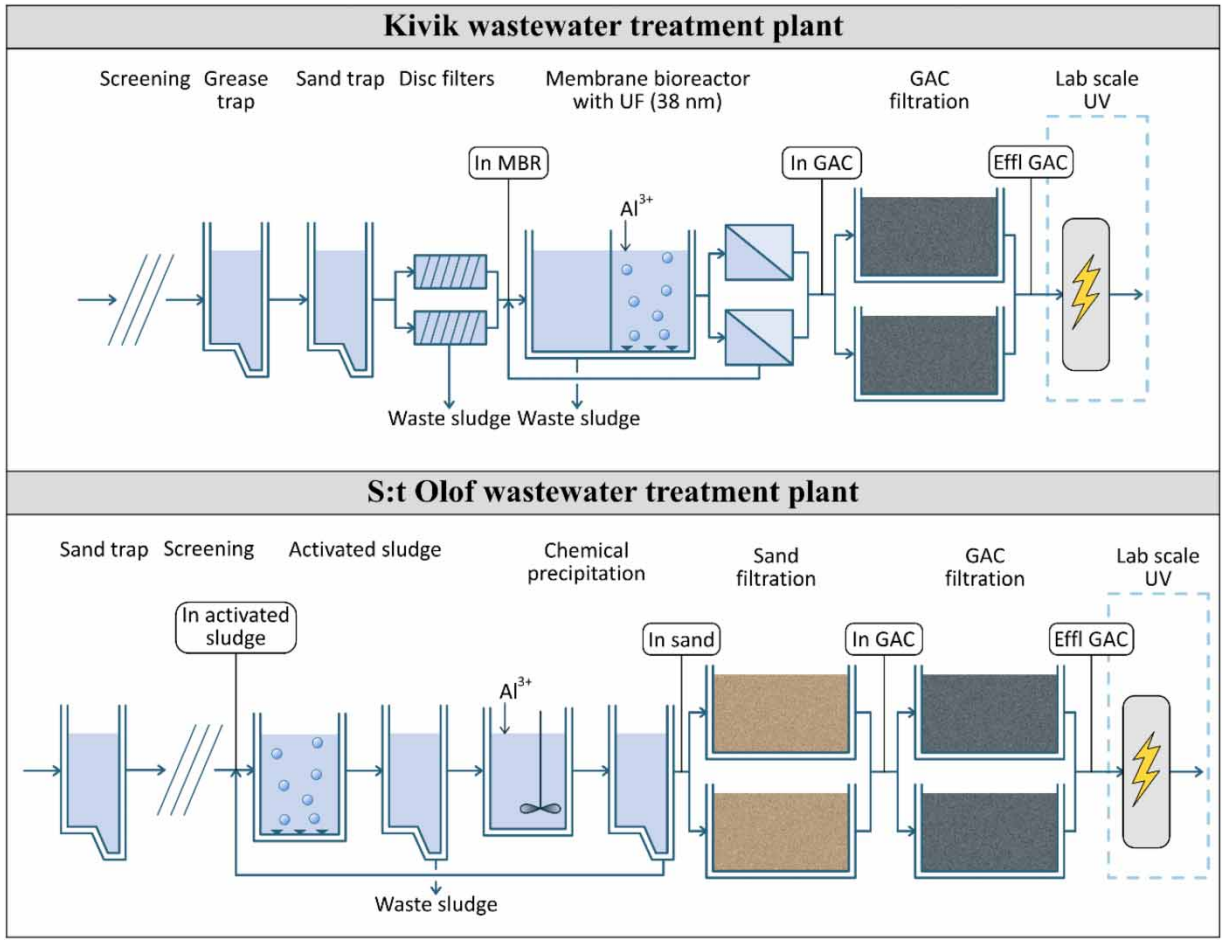


Figure 1 | Process schemes with sampling points for Kivik WWTP (top) and S:t Olof WWTP (bottom).

Table 1 | Experimental parameters for the UV disinfection experiments

			Intended UV fluence					
			200 J/m^2		400 J/m^2		700 J/m^2	
WWTP	Date	UV transmittance (UVT) (%)	Flow rate (L/s)	UV fluence (J/m^2)	Flow rate (L/s)	UV fluence (J/m^2)	Flow rate (L/s)	UV fluence (J/m^2)
Kivik	2023-06-12	84	0.346	202	0.156	450	0.100	702
Kivik	2023-06-26	82	0.349	197	0.161	428	0.096	719
Kivik	2023-10-02	85	0.315	225	0.159	447	0.102	699
S:t Olof	2023-06-12	83	0.349	198	0.158	437	0.100	691
S:t Olof	2023-06-26	81	0.348	192	0.154	432	0.094	707
S:t Olof	2023-10-02	81	0.326	204	0.159	419	0.099	675

2.3. Analytical methods

2.3.1. Microbial analysis

Microbial analysis (*E. coli*, total coliform bacteria, and total cell concentration (TCC)) was conducted in-house, with select analyses conducted by an external accredited service (Eurofins, heterotrophic plate count (HPC), slow-growing bacteria, *C. perfringens*, intestinal enterococci, yeast, mold fungi, and actinomycetes). All methods are presented in Table S3. The in-house microbial analysis was performed on all samples, while the more detailed microbial analysis conducted by the service laboratory encompassed the sand and GAC influents and effluents from S:t Olof WWTP, and the GAC influent and effluent from Kivik WWTP. Samples for the accredited service laboratory were stored in 500 mL bottles that contained 10 mg thiosulfate. All samples were stored in the dark at 6–9°C and sent within 24 h, except those from the first sampling occasion, which were sent within 4 days.

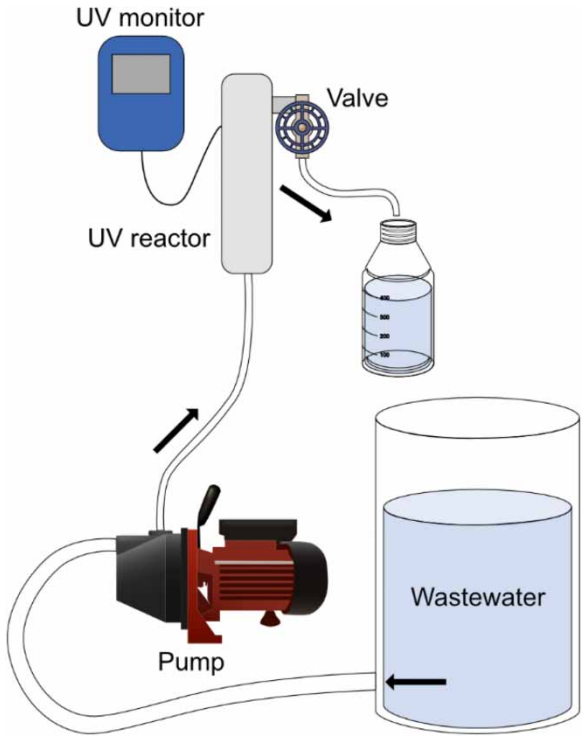


Figure 2 | Schematic of the UV equipment.

E. coli and total coliform bacteria were analyzed within 48 h from sampling, with IDEXX Colilert 18 and Quanti-Tray 2000, per the manufacturer's instructions. The influents from both WWTPs were diluted 1:100,000 with drinking water prior to analysis. The sand and GAC influents from S:t Olof WWTP were diluted 1:1,000.

E. coli and total coliform concentrations were measured both internally, on the day of the experiments, and by the external laboratory, allowing for control of potentially deviating results due to, for example, continued growth of the bacteria. No substantial deviations were observed (Table S2).

TCC was analyzed using flow cytometry (FCM) on a BD Accuri C6 Plus. The influents to both WWTPs were passed through a 10 μm filter prior to analysis to protect the instrument from clogging and were then diluted 1:10 due to high cell counts. SYBR® Green I (dilution: 100× in dimethyl sulfoxide and final concentration in samples: 1×) was used to measure TCC, and the samples were incubated at 37°C for 15 min after staining. Fifty microliter of sample was analyzed at a flow of 35 mL/min (except for the influent to S:t Olof WWTP, for which 25 μL of sample was analyzed on the last occasion due to high cell counts). The samples were analyzed in duplicate and the average of the resulting values was used for the data analysis. The flow cytometric analysis was conducted within 24 h from sampling.

2.3.2. Chemical analysis

The chemical analysis was performed in-house (dissolved organic carbon (DOC), PO_4^{3-}–P, NO_3^-–N, NO_2^-–N, NH_4^+–N, and conductivity). Additional chemical analysis of 114 parameters in the Swedish drinking water legislation was performed on one sample (Kivik 400 J/m^2 from October 2). This sample was selected based on previous experiments and microbial analysis and the additional chemical analysis was conducted at the same accredited laboratory as the microbial analysis (Eurofins; the methods are presented in Table S3). In total, 400 J/m^2 is a commonly used UV fluence for drinking water production in Sweden (Saguti *et al.* 2022) and the sample thus represents a standard scenario.

In-house analysis of DOC, nitrogen, and phosphorus fractions were performed within 24 h from sampling. The samples were filtered (0.45 μm, GVS filter technology) and stored in the dark at 6–9°C prior to analysis. The nitrogen and phosphorus fractions were analyzed on a Metrohm Eco Ion chromatograph and DOC was analyzed using a Shimadzu (TOC-L). In addition, turbidity and suspended solids were measured, resulting in 132 parameters that were analyzed in the Kivik 400 J/m^2 sample.

3. RESULTS AND DISCUSSION

3.1. Evaluation of wastewater treatment processes upstream UV disinfection

When comparing influent and effluent concentrations, the log removal value (LRV) of both *E. coli* and total coliform bacteria was higher at Kivik WWTP (6.8 for *E. coli* and 6.7 for total coliform bacteria) compared with S:t Olof WWTP (a LRV of 3.9 for both *E. coli* and total coliform bacteria) (Figure 3). This can be attributed to the MBR at Kivik WWTP, which contributed most to the log removal (6.1 and 5.7, respectively). At S:t Olof WWTP, the largest contribution to the total LRV was from the CAS process (2.7 for *E. coli* and 2.6 for total coliform bacteria). TCC decreased slightly in both treatment plants (Figure 3).

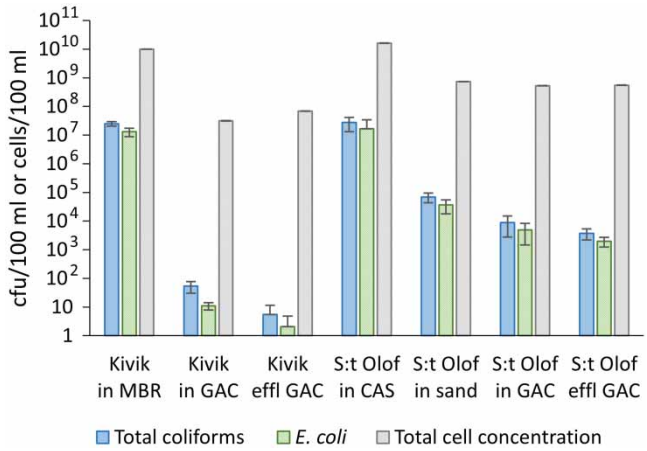


Figure 3 | *E. coli*, total coliform bacteria, and TCC through Kivik and S:t Olof WWTPs.

GAC filtration increases total bacteria concentrations (Wilcox *et al.* 1983; Miller *et al.* 2020; Takman *et al.* 2023) but has been shown to selectively decrease the concentrations of *E. coli* and total coliform bacteria (El-Zanfaly *et al.* 1998; Hijnen *et al.* 2010; Spit *et al.* 2022), as observed in our study. Examining only the influents to and effluents from the GAC filters, the LRV was 0.7 for *E. coli* and 1.0 for total coliform bacteria at Kivik WWTP, versus 0.4 for both *E. coli* and total coliform bacteria at S:t Olof WWTP – demonstrating a similar but slightly higher removal in the GAC filter at Kivik WWTP. Many factors could contribute to this pattern, such as differences in operational conditions (for example, EBCT, Table S1) or in upstream treatment processes, causing variations in nutrient, carbon, and bacterial loads and composition.

The *E. coli* and total coliform concentrations in both WWTP effluents exceeded the limits defined in the Swedish drinking water criteria (present in 100 mL) (LIVSFS 2022:12). The average *E. coli* concentration in the Kivik WWTP effluent was 2 cfu/100 mL, meeting the quality class A criteria (<10 cfu/100 mL) for irrigation per Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse. The average effluent *E. coli* concentration from S:t Olof WWTP was 1967 cfu/100 mL, exceeding the limits for quality class C water on all occasions and meeting the criteria for quality class D.

Quality class A water can be used for the irrigation of 'all food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw' whereas water that is deemed quality class D can be used for irrigation of 'industrial, energy and seeded crops' (Regulation (EU) 2020/741, Annex I).

Previous studies (Takman *et al.* 2023) have reported that the concentrations of *E. coli* in the effluent from the MBR + GAC process at Kivik WWTP sometimes failed to pass the class A criteria, meeting only quality class B standards. However, these measurements were conducted in 2021 and more recent measurements conducted by the water utility during 2023 and 2024 show that concentrations for quality class A were achieved.

The average effluent turbidity was ≤1 NTU and the suspended solids concentration in the effluent was <1 mg/L for both WWTPs (Table 2). The effluent conductivity was 787 µS/cm at Kivik WWTP and 649 µS/cm at S:t Olof WWTP.

Different trends were observed between Kivik WWTP and S:t Olof WWTP for the removal of *C. perfringens* and enterococci, with a higher removal in the Kivik GAC filter versus the sand and GAC filters at S:t Olof WWTP (Figure 4).

The differences in bacterial removal in the GAC and sand filters could be due to differences in the composition of the biofilm, which seem to prevent the growth of *C. perfringens* and intestinal enterococci in the Kivik GAC filters to a greater extent than in the S:t Olof sand and GAC filters. The biofilm composition and function may be affected by several factors, such as the influent concentration and composition of microorganisms, DOC, and nutrients – and thus by the upstream treatment processes (Li *et al.* 2014; Vignola *et al.* 2018; Dottorini *et al.* 2021).

The concentrations of culturable microorganisms (that is, not the total number of cells as determined by FCM) were higher in the sand and GAC influents at S:t Olof WWTP compared with the GAC influent at Kivik WWTP, likely due to the UF process upstream of the GAC filters at Kivik WWTP (Table 3). All microbial concentrations (except that of Actinomycetes, which were consistently ≤1 cfu/100 mL) decreased over the Kivik GAC filter, whereas some concentrations increased over the S:t Olof GAC filter (Table 3). The concentrations in the GAC effluents of most microbial parameters exceeded the limits in the Swedish drinking water criteria (LIVSFS 2022:12) (Table 3). The GAC filter downstream of the MBR removed *E. coli*, total coliform

Table 2 | General performance parameters: Kivik and S:t Olof WWTPs

	DOC mg/L	NH_4^+ mg N/L	NO_3^-	NO_2^-	PO_4^{3-} mg P/L	Suspended solids mg/L	Turbidity NTU	Conductivity µS/cm
Kivik in MBR	22.9	29.7	2.8	0.3	3.0	52	25	
Kivik in GAC	4.6	0.04	23.6	nd	0.2	<1	<1	
Kivik effl GAC	3.5	0.04	25.5	0.06	0.2	<1	<1	787[a]
S:t Olof in CAS	37.5	24.5	3.8	0.6	2.9	191	161	
S:t Olof in sand	6.5	1.2	20.5	0.45	nd[b]	7	3	
S:t Olof in GAC	5.9	0.8	21.6	0.03	nd[b]	1	1	
S:t Olof effl GAC	4.5	0.6	22.2	0.05	nd[b]	<1	<1	649[a]

Note: Internal analysis. Average of all three sampling occasions.

[a]Measured on 2023-10-02.

[b]nd = not detected.

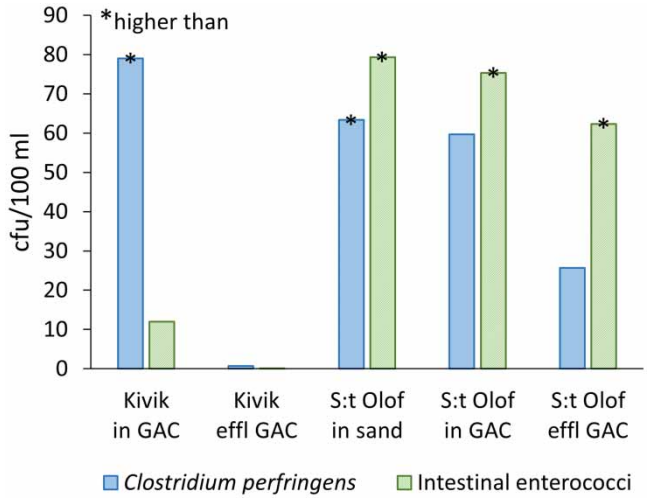


Figure 4 | Concentrations of *C. perfringens* and intestinal enterococci through Kivik and S:t Olof WWTPs. *Higher than: one or more of the concentrations exceeded the upper limit of quantification (LOQ; 100 cfu/100 mL) and the LOQ was used to calculate the average values.

Table 3 | Concentrations of microbial parameters in influents to and effluents from the Kivik and S:t Olof sand and GAC filters, compared with Swedish drinking water regulations (LIVSFS 2022:12)

Swedish drinking water criteria (LIVSFS 2022:12)		HPC (cfu/mL) No unusual change	Slow-growing bacteria (cfu/mL) No unusual change	*Clostridium perfringens* (cfu/100 mL) Present	Intestinal enterococci (cfu/100 mL) Present	Microfungi (cfu/100 mL) 100 cfu/100 mL	Actinomycete (cfu/100 mL) 100 cfu/100 mL
Kivik in GAC	2023-06-12	>5,000	>5,000	68	4	25	<1
	2023-06-26	110	250	69	15	29	<1
	2023-10-02	141	174	>100	17	50	1
Kivik effl GAC	2023-06-12	170	190	<1	<1	4	<1
	2023-06-26	4	25	2	<1	5	<1
	2023-10-02	45	76	<1	1	37	<1
S:t Olof in sand	2023-06-12	>5,000	>5,000	5	48	533	<1
	2023-06-26	1,840	2,510	85	>100	15	<1
	2023-10-02	>5,000	>5,000	>100	90	292	<1
S:t Olof in GAC	2023-06-12	1,400	>5,000	65	36	256	<1
	2023-06-26	3,100	>5,000	79	>100	38	<1
	2023-10-02	3,360	>5,000	35	90	>1,000	<1
S:t Olof effl GAC	2023-06-12	310	410	14	45	19	<1
	2023-06-26	280	390	49	>100	129	<1
	2023-10-02	1,000	1,460	14	42	304	<1

Notes: In GAC: influent to GAC filter; effl GAC: effluent from GAC filter; in sand: influent to sand filter. Microfungi was calculated as the sum of yeast and mold fungi concentrations.

bacteria, *C. perfringens*, and intestinal enterococci to a higher degree than the GAC filter downstream of the CAS + sand process. This indicates that the processes upstream of GAC filters influence their removal capacity and that GAC filters perform better, regarding removal of microbial contaminants, downstream of an MBR versus a CAS + sand process. The effluent microbial concentrations, however, demonstrate that disinfection is necessary to ensure a high microbial water quality.

3.2. UV disinfection experiments

In the GAC effluents, the concentration of Actinomycetes was the only microbial parameter in the Swedish drinking water criteria (LIVSFS 2022:12) that was met on all occasions (Table 3). The limits for *C. perfringens*, *E. coli*, total coliform bacteria, intestinal enterococci, and microfungi (sum of yeast and mold fungi) were exceeded in several samples. Thus, these parameters

were analyzed in the UV disinfection experiments. As the microbial water quality monitoring conducted in this study was only based on a few occasions, it is not possible to draw any conclusions on 'unusual changes' for the HPC and slow-growing bacteria.

A high inactivation, that is, a disabling of growth, of *E. coli*, total coliform bacteria, and intestinal enterococci in water can be achieved with UV radiation (Sommer *et al.* 2000; Jacangelo *et al.* 2003; Mezzanotte *et al.* 2007). Similar results were yielded in the present study, in which a UV fluence of 200 J/m^2 was sufficient to obtain concentrations <1 cfu/100 mL for these microbial indicators in the Kivik (MBR + GAC) and S:t Olof (CAS + sand + GAC) effluents, meeting quality class A criteria for irrigation and Swedish drinking water criteria (Table 4). Inactivation of *C. perfringens* and microfungi requires higher UV fluence (Hijnen *et al.* 2006; Carabias *et al.* 2023), consequently, in our study, the concentration of *C. perfringens* was not consistently lowered to <1 cfu/100 mL by any UV fluence in the CAS + sand + GAC effluent. The concentrations in the MBR + GAC effluent before UV exposure, however, were low (≤2 cfu/100 mL) and a UV fluence of 200 J/m^2 was sufficient to achieve concentrations that were consistently <1 cfu/100 mL.

Microfungi were detected in the effluents from both WWTPs after exposure to all UV fluences, but following exposure to UV fluences >400 J/m^2, these concentrations did meet the drinking water criteria (<100 cfu/100 mL). The HPC and slow-growing bacteria concentrations in the CAS + sand + UV effluent (S:t Olof WWTP) varied between <1 cfu/mL and approximately 160 cfu/mL, corresponding to a range of at least two orders of magnitude. This variation could be considered wide, but since the concentrations of *C. perfringens* and microfungi in these samples exceeded the drinking water limits, the exact definition of 'no unusual change' is not crucial for the conclusions.

In the Kivik samples exposed to 200 J/m^2 fluence, the limit for microfungi was exceeded on the last occasion. The concentration of 550 cfu/100 mL is, however, difficult to explain with the concentration from the upstream GAC effluent of

Table 4 | Concentrations of microbial parameters before and after UV disinfection

Swedish drinking water criteria (LIVSFS 2022:12)		HPC (cfu/mL) No unusual change	Slow-growing bacteria (cfu/mL) No unusual change	*Clostridium perfringens* (cfu/100 mL) Present	Intestinal enterococci (cfu/100 mL) Present	Microfungi (cfu/100 mL) 100 cfu/100 mL	*E. coli* (cfu/100 mL) Present	Total coliform bacteria (cfu/100 mL) Present
Kivik effl GAC	2023-06-12	170	190	<1	<1	4	<1	1
	2023-06-26	4	25	2	<1	5	5	12
	2023-10-02	45	76	<1	1	37	1	3
Kivik 200 J/m^2	2023-06-12	<1	No data	<1	<1	5	<1	<1
	2023-06-26	1	23	<1	<1	27	<1	<1
	2023-10-02	5	13	<1	<1	550	<1	<1
Kivik 400 J/m^2	2023-06-12	<1	<1	<1	<1	1	<1	<1
	2023-06-26	<1	2	<1	<1	8	<1	<1
	2023-10-02	3	4	<1	<1	53	<1	<1
Kivik 700 J/m^2	2023-06-12	<1	<1	<1	<1	<1	<1	<1
	2023-06-26	<1	1	<1	<1	4	<1	<1
	2023-10-02	1	1	<1	<1	3	<1	<1
S:t Olof effl GAC	2023-06-12	310	410	14	45	19	2,700	5,300
	2023-06-26	280	390	49	>100	129	2,000	3,700
	2023-10-02	1,000	1,460	14	42	304	1,200	2,200
S:t Olof 200 J/m^2	2023-06-12	<1	<1	7	<1	4	<1	<1
	2023-06-26	157	165	11	<1	45	<1	<1
	2023-10-02	6	6	4	<1	107	<1	<1
S:t Olof 400 J/m^2	2023-06-12	<1	<1	6	<1	2	<1	<1
	2023-06-26	<1	4	4	<1	8	<1	<1
	2023-10-02	1	6	2	<1	78	<1	<1
S:t Olof 700 J/m^2	2023-06-12	<1	3	<1	<1	4	<1	<1
	2023-06-26	<1	<1	<1	<1	3	<1	<1
	2023-10-02	2	1	1	<1	30	<1	<1

Notes: Effl GAC: effluent from GAC filter. Microfungi is calculated as the sum of yeast and mold fungi.

37 cfu/100 mL. It seems likely that the sample was contaminated during transport or analysis, or that the fungi were able to continue growing between the time of the sampling and the analysis. Due to technical errors by the external laboratory, there was no analysis reported for slow-growing bacteria in the Kivik 200 J/m^2 sample from June 12, 2023. Other than the high microfungi concentration in the Kivik 200 J/m^2 sample, all concentrations in the UV-treated MBR + GAC effluent samples (Kivik WWTP) met the Swedish drinking water criteria after exposure to all UV fluences. The TCC in the Kivik GAC effluent varied between 500,000 and 900,000 cells/mL. While in the higher range of TCC reported for drinking water, this is not unprecedented (Schleich *et al.* 2019; Rosenqvist *et al.* 2023). All cells in the water are affected by, and absorb, UV irradiation, and the results therefore confirm that the studied UV fluences are sufficient to treat the WWTP effluents to the extent that they meet microbial drinking water criteria also with these cell concentrations. It should be noted, however, that the hydraulics in the UV reactor, including variables such as the orientation of the reactor, mixing, and potential turbulence, can affect the disinfection efficiency (Ho *et al.* 1998). Thus, additional assessments of the impact of different UV fluences at full scale will be required to validate the results reported here for laboratory-scale UV disinfection.

3.3. Evaluation of chemical drinking water quality

Treatment of the effluent from Kivik WWTP (MBR + GAC) with UV fluence >400 J/m^2 resulted in water that fulfilled the Swedish criteria for microbial drinking water quality and thus, one of these samples (from October 2, 2023) was selected for extensive chemical analysis, comprising 114 parameters from the Swedish criteria (the results are presented in Table S4). The parameters included metals, pesticides, per- and polyfluoroalkyl substances (PFAS), trihalomethanes (THMs), and polycyclic aromatic hydrocarbons.

The concentrations of all chemical parameters in the UV-treated effluent met the drinking water criteria, except nitrate (Table S4). In the effluent from an activated sludge process with denitrification, however, the nitrate concentration would likely meet the criteria. A selection of the chemical parameters is presented in Table 5, together with their limits and indicator values.

The concentration of PFAS 4 (2.9 ng/L, the sum of perfluorooctane sulfonate (PFOS), perfluorooctanoate (PFOA), perfluorononanoate (PFNA), and perfluorohexane sulfonate (PFHxS); Table S4) approached the limit (4.0 ng/L) in the Swedish criteria. Given the substantial seasonal variations in flow previously reported at Kivik WWTP (Takman *et al.* 2023) the concentrations of all water quality parameters will likely vary throughout the year, potentially causing concentrations that exceed the criteria. The examined sample was collected during a period of low flow (Figure S1), and it is thus likely that contaminants in the water will generally be more diluted during the remainder of the year, which would decrease their concentrations. Nevertheless, several samples, collected over a longer period, should be examined with a similar chemical panel to ensure that concentrations of key parameters are consistently meeting the drinking water criteria.

In addition, there are no limits on the levels of pharmaceuticals in Swedish drinking water criteria. These substances could be present in higher concentrations in wastewater compared with groundwater and surface water, which are currently used in conventional drinking water production in Sweden. Concerning the potable reuse of wastewater, it should, therefore, be examined whether the drinking water criteria need to be updated with such compounds. Drinking water quality is further defined as follows (translated from Swedish):

> '**6 §** Drinking water should be healthy and pure. Drinking water is considered healthy and pure if it
>
> 1. Does not contain microorganisms, parasites and substances in numbers or levels that pose a risk to human health, and
> 2. Meets the criteria in appendix 1' (LIVSFS 2022:12),

Table 5 | A selection of chemical parameters measured in the Kivik effluent treated with a UV fluence of 400 J/m^2

Parameter	Unit	Concentration in Kivik 400 J/m^2	Limit or indicator value (LIVSFS 2022:12)
Sum THM	µg/L	<4.0	100
Sum PFAS 4	ng/L	2.9	4.0
Sum PFAS 21	ng/L	19	100
Sum pesticides	µg/L	Not detected	0.50

where the criteria in Appendix 1 correspond to the limits in Tables 3–5, and S4. Point 2 above can be achieved through accredited analysis of all parameters in the appendix, whereas Point 1 is more complex, since many chemicals could be present in groundwater, surface water, and perhaps especially in wastewater, even though they are not included in the analysis. Treatments that target a broad range of chemical and microbial pollutants, such as GAC filtration and UV disinfection, remove a spectrum of pollutants from the water, but do not guarantee that all harmful pollutants are sufficiently eliminated. One complementary strategy to chemical analysis for discovering unknown pollutants could be to apply effect-based methods, as discussed by Dingemans *et al.* (2019). Concentrations and removal of key viruses should also be considered, as conventional UV fluences have sometimes been inefficient for their inactivation in drinking water (Saguti *et al.* 2022).

4. CONCLUSIONS

Full-scale GAC filtration at two WWTPs, followed by UV disinfection conducted at the laboratory scale, was examined to determine the influence of upstream treatment (MBR and CAS followed by sand filtration) on the GAC and UV treatment capacities. The implications of this on wastewater reuse were analyzed by comparing effluent water quality to criteria for wastewater to be reused for irrigation, and to drinking water criteria. Three UV fluences (approximately 200, 400, and 700 J/m^2) were evaluated, and based on the UV laboratory experiments, one sample (MBR + GAC effluent treated with a UV fluence of 400 J/m^2) was selected for extensive chemical analysis, comprising over 100 parameters in Swedish drinking water legislation. The following conclusions were drawn:

- *E. coli*, total coliform bacteria, *C. perfringens*, and intestinal enterococci were removed to a higher extent in the GAC filter that followed downstream of an MBR, compared to the GAC filter that followed downstream of a CAS process and sand filtration.
- Based on an extensive microbial and chemical analysis (approximately 130 parameters), drinking water quality was achieved per Swedish criteria in the MBR + GAC effluent that was treated with a UV fluence of 400 J/m^2, with the sole exception being nitrate. High nitrate concentrations can be mitigated with a biological wastewater treatment process with denitrification.
- With the two higher UV fluences (400 and 700 J/m^2), microbial drinking water criteria were met after UV disinfection of the MBR + GAC effluent.
- Without UV disinfection, the MBR + GAC effluent met the criteria for quality class A water for irrigation (Regulation (EU) 2020/741) on all occasions, whereas the CAS + sand + GAC effluent met the criteria for quality class D water.
- The concentrations of *E. coli*, total coliform bacteria, and intestinal enterococci were <1 cfu/100 mL at UV fluences $\geq$200 J/m^2, regardless of the upstream treatment processes.

ACKNOWLEDGEMENTS

The project was conducted within the ÅÄÖ Project, which was funded by Formas – a Swedish Research Council for Sustainable Development (No. 2021-02656). Further, the Agenda 2030 Graduate School at Lund University is gratefully acknowledged for its financial support. The authors thank Ronny Helgesson at Österlen VA for assistance with sampling.

FUNDING

The project was funded by Formas – a Swedish Research Council for Sustainable Development (No. 2021-02656), and by the Agenda 2030 Graduate School at Lund University. Formas and the Agenda 2030 Graduate School had no involvement in the study design, the collection, analysis or interpretation of data, the writing, or in the decision to submit the article for publication.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 22 December 2023; accepted in revised form 10 March 2024. Available online 21 March 2024