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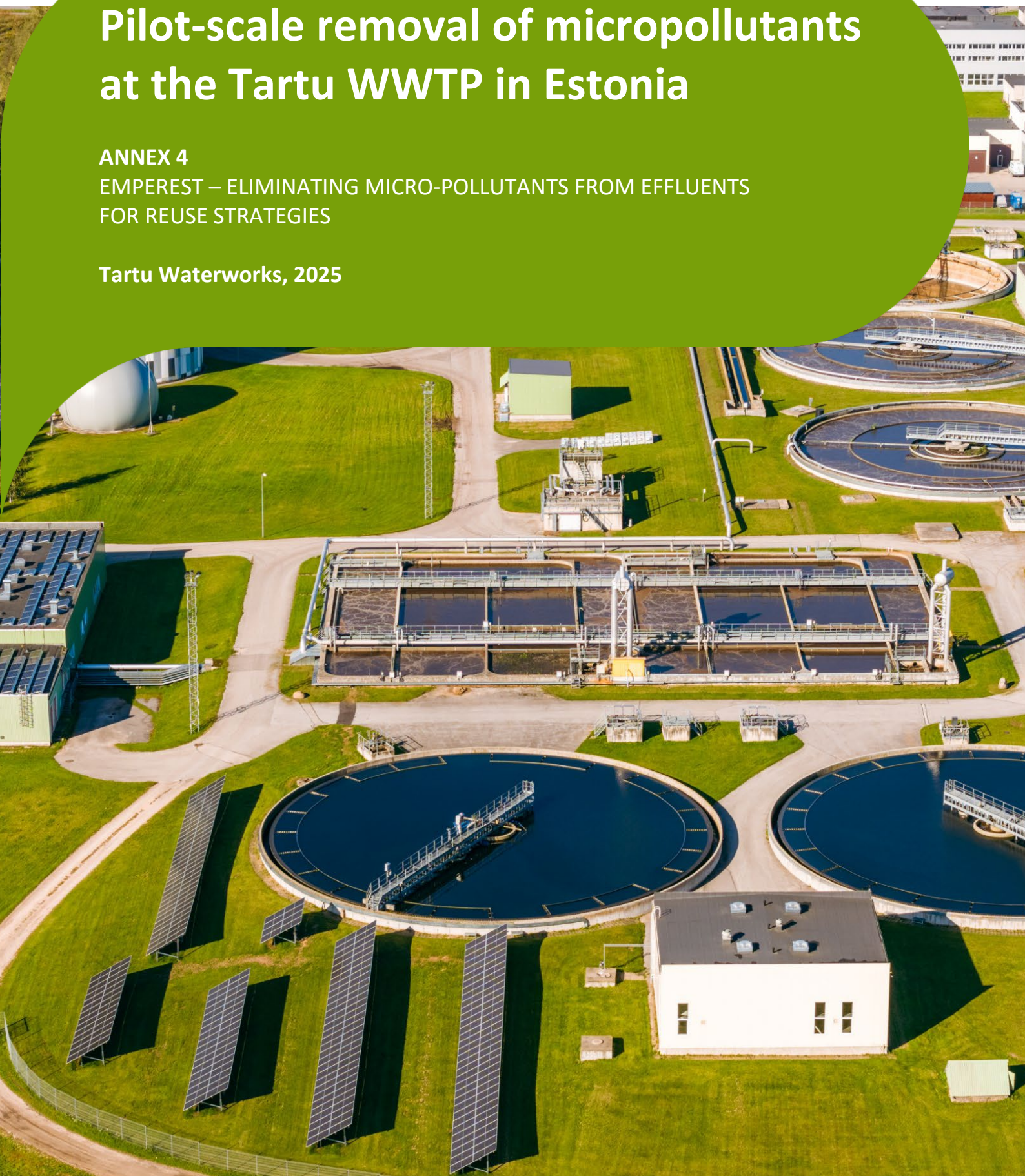
EMPEREST

Pilot-scale removal of micropollutants at the Tartu WWTP in Estonia

ANNEX 4
EMPEREST – ELIMINATING MICRO-POLLUTANTS FROM EFFLUENTS FOR REUSE STRATEGIES

Tartu Waterworks, 2025



Imprint

This publication has been developed within the project **EMPEREST – Eliminating Micro-Pollutants from Effluents for Reuse Strategies,** co-financed by the Interreg Baltic Sea Region Programme 2021–2027, and helping to drive the transition to a green and resilient Baltic Sea region.

This report forms Annex 4 of the overarching study "Strategies and technological means for minimising organic micropollutant emissions from WWTPs". Each annex presents a site-specific sub-study conducted within the broader framework.

EMPEREST consortium: Union of the Baltic Cities Sustainable Cities Commission c/o City of Turku (FI), Baltic Marine Environment Protection Commission – Helsinki Commission (HELCOM) (FI), University of Tartu (EE), Berlin University of Technology (DE), Turku University of Applied Sciences (FI), Gdańsk Water Utilities (PL), Water and Sewage Company Ltd of Szczecin (PL), Tartu Waterworks Ltd (EE), Tallinn Water Ltd (EE), "Kaunas water" Ltd (LT), Turku Region Wastewater Treatment Plant (FI), DWA German Association for Water, Wastewater and Waste DWA Regional group North-East (DE), Environmental Centre for Administration and Technology (LT), City of Riga (LV).

Contract: EMPEREST – Eliminating Micro-Pollutants from Effluents for Reuse Strategies no. C013

Title: Strategies and technological means for minimising organic micropollutant emissions from WWTPs

Pilot-scale removal of micropollutants at the Tartu WWTP in Estonia

Version: v. 1.0, September 2025

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Project note

The EMPEREST project supports local authorities, service providers and policy-making community in finding ways to reduce PFAS (Per- and polyfluoroalkyl substances) and other organic micropollutants from the water cycle. The project has four activity strands to fulfil its aims. First, in close cooperation with HELCOM, EMPEREST prepares methodological recommendations to monitor PFAS group in the aquatic environment. Second, local authorities address the subject on the city level by developing a PFAS risk assessment framework to identify and assess PFAS-related risks and propose relevant risk mitigation strategies. Third, EMPEREST supports water utilities in making informed decisions about cost-effective treatment strategies and investments for removing micropollutants from wastewater. Finally, capacity building takes place for both local authorities and public service providers to inform them about the recent developments in the field and train them with tailored materials and tools.

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List of Abbreviations

AOP	advanced oxidation process
A2/O	anaerobic/anoxic/oxic system
BOD_7	biochemical oxygen demand
COD	chemical oxygen demand
dNF	direct nanofiltration
DOC	dissolved organic carbon
DOM	dissolved organic matter
EBCT	empty bed contact time
EU	European Union
GAC	granular activated carbon
HMI	Human-Machine Interface
NF	nanofiltration
OMPs	organic micropollutants
PCBs	polychlorinated biphenyls
PCMF	pile cloth media filtration
PE	population equivalent
PFAS24	list of twenty four PFAS compounds
PFBA	perfluorobutanoic acid
PFBS	perfluorobutane sulfonic acid
PFDA	perfluorodecanoic acid
PFDoDA	perfluorododecanoic acid
PFDoDS	perfluorododecane sulfonic acid
PFDS	perfluorodecane sulfonic acid
PFHpA	perfluoroheptanoic acid
PFHpS	perfluoroheptane sulfonic acid
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexane sulfonic acid
PFNA	perfluorononanoic acid
PFNS	perfluorononane sulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonic acid
PFPeA	perfluoropentanoic acid
PFPeS	perfluoropentane sulfonic acid
PFTrDA	perfluorotridecanoic acid
PFTrDS	perfluorotridecane sulfonic acid
PFUnDA	perfluoroundecanoic acid
PFUnDS	perfluoroundecane sulfonic acid
PSA	pressure swing adsorption
SAC 254	Spectral Absorption Coefficient measured at a wavelength of 254 nanometers
SCADA	Supervisory Control and Data Acquisition
sPAC	superfine powdered activated carbon
SS	suspended solids
TCOD	total chemical oxygen demand
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
UV	ultraviolet
UWWTD	urban wastewater treatment directive
VPN	Virtual Private Network
WWTPs	wastewater treatment plants

1. Introduction

Organic micropollutants (OMPs) in wastewater are an increasingly recognized environmental and public health concern due to their widespread presence and adverse effect on human health and the environment. OMPs are defined as trace-level contaminants, typically present in very low concentrations ranging from nanograms to micrograms per litre. They originate from various industrial and anthropogenic sources and pose significant ecological and health challenges due to their persistence, bioaccumulation potential, and biological activity at low concentrations.

Wastewater treatment plants (WWTPs) are among the principal point sources of OMPs. Although modern WWTPs are effective at removing conventional pollutants such as organic matter, nitrogen, and phosphorus, they often fall short in eliminating OMPs. This shortcoming is due to the diverse chemical structures and properties of OMPs, which make them resistant to traditional treatment processes. As a result, effluents discharged from WWTPs may still contain a cocktail of biologically active compounds that can disrupt aquatic ecosystems and pose long-term health risks to humans through environmental exposure.

The persistence of OMPs in treated wastewater underscores the urgent need for both technological and regulatory advancements. Advanced treatment methods such as ozonation, membrane filtration, nanofiltration, powdered and/ or activated carbon adsorption, are being actively researched and piloted to address this challenge. These technologies aim to complement existing wastewater treatment processes by targeting and degrading or capturing micropollutants before discharge. However, scaling up these solutions requires careful evaluation of their efficiency, cost, and environmental sustainability.

To better protect human health and the environment, in November 2024, the European Union (EU) adopted the revised Urban Wastewater Treatment Directive (UWWTD), which mandates enhanced nutrient removal and imposes stricter requirements for monitoring and eliminating micropollutants from urban wastewater (European Union, 2024). Urban WWTPs serving 150,000 population equivalents (PE) or more must implement quaternary treatment to remove a broad spectrum of micropollutants by 2045. The UWWTD also imposes additional quaternary treatment in WWTPs serving agglomerations between 10,000 and 100,000 PE in areas identified as sensitive to micropollutant pollution, unless a comprehensive risk assessment shows no significant public or ecological risk.

This report presents the results of pilot testing on the removal of organic micropollutants by means of a mobile pilot-scale plant, designed to evaluate the efficiency of advanced wastewater treatment processes. The aim of the pilot tests was to assess the potential of ozone oxidation, activated carbon adsorption, superfine activated carbon adsorption and nanofiltration for reducing micropollutant emissions in treated wastewater, as well as to determine the process parameters that ensure the highest removal efficiency. The results of the pilot test will contribute to the development of evidence-based strategies for the broader implementation of advanced treatment technologies, ultimately supporting the EU's objectives of safeguarding water quality, protecting aquatic ecosystems, and minimizing human health risks associated with micropollutant exposure.

2. Setup

2.1. Study site

The pilot test was carried out at Tartu WWTP, Estonia's second-largest municipal WWTP, which discharges its treated effluent into the Emajõgi River, eventually reaching the Baltic Sea via Lake Peipsi and the Narva River. The plant receives mostly municipal wastewater and has an average influent flow rate of approximately 25 000 m^3/day (in dry weather conditions). The pollutant load entering the plant corresponds to approximately 150 000 PE.

The primary treatment includes two screens in the main pumping station and two screens after Tähe pumping station. After that wastewater enters two aerated grit chambers (max. 6), and one primary settling tank. The biological treatment is activated sludge treatment, configured according to the Anaerobic/ Anoxic/ Oxic (A2O) system, and two secondary clarifiers.

Tertiary treatment step includes three discfilters, after which the effluent flows to river Emajõgi.

Average concentrations of pollutants in the effluent (after discfilters) are as follows:

- Biochemical oxygen demand (BOD_7) 1.8 mg BOD_7/L
- Chemical oxygen demand (COD) 24.8 mg COD/L
- Total suspended solids (TSS) 3.4 mg/L
- Total nitrogen (TN) 7.0 mg N/L
- Total phosphorus (TP) 0.3 mg P/L

2.2. Pilot plant description

2.2.1. Introduction to the process

The pilot test was conducted using two mobile pilot containers, designed and built by Industrial System Engineering, based on a detailed design concept developed collaboratively by Tartu Waterworks Ltd and the University of Tartu (**Figure 1** and **Figure 2**).

Figure 1. View of the pilot plant (two sea containers) located at the Tartu WWTP in Estonia

Figure 2. View of the pilot plant interior

The pilot plant is dedicated to evaluating the removal efficiency of OMPs from water or wastewater.
For the pilot testing, Tartu Waterworks used effluent water from the WWTP i.e, the outflow from the discfilters as the inlet for the pilot equipment.
According to the process scheme (Figure 3), the testing equipment is divided into units corresponding to different technological systems.

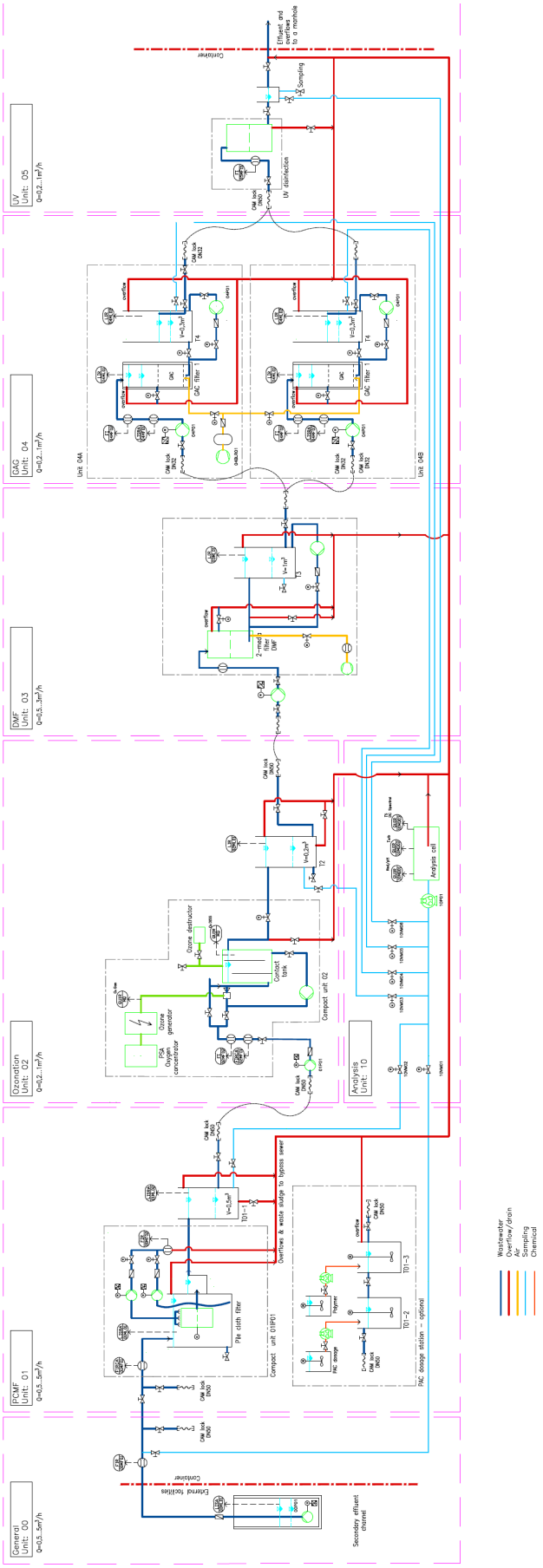

Figure 3. Process scheme of the pilot constructed in Tartu

Effluent of the WWTP is pumped to the first unit, which corresponds to pile cloth media filtration (PCMF). In Tartu pilot, Mecana PCMF, which uses drum filter, was tested out. The main aim of the PCMF unit is to remove suspended solids from the water as it flows through the filter cloth into the filter drum, the solids being retained on the filter cloth. The filtered water then flows out of the unit through the rising chamber and finally over an overflow weir to the buffer tank (Mecana Umwelttechnik AG, 2023). Effluent of PCMF is used in the following technological units of the pilot plant.

The second unit represents the ozonation system, recognized as one of the advanced treatment technologies for eliminating persistent organic micropollutants (OMPs), including pharmaceutical residues. Through oxidation, ozone transforms these contaminants into less harmful substances. The system's ozone consumption is influenced by the specific types and concentrations of pollutants present in the WWTP effluent (Kuusik et al., 2023).

This ozonation system employs pressure swing adsorption (PSA) technology to generate high-purity oxygen on-site. Ambient air is passed through a PSA oxygen generator, which uses selective adsorbents to separate oxygen from other gases. The extracted oxygen is then supplied to the ozone generator, where ozone is produced. To maintain optimal operating temperatures and ensure consistent ozone production, the ozone generation cells are cooled using a closed-circuit water cooling system. The generated ozone is subsequently injected into the WWTP's effluent stream, where it dissolves and reacts with OMPs, effectively degrading them (Berat, 2025; United States Environmental Protection Agency, 1999).

Ozone treated water then proceeds to the third unit, the sand filter (DMF). In Tartu pilot system, the sand filter operates in a downward flow direction during normal filtration, effectively removing any remaining suspended solids and mineral residues. During the backwash cycle, the flow is reversed, i.e water and air is pumped upward to clean the filter media, and the resulting dirty backwash water is discharged through an upper outlet pipe.

Following the sand filter, a buffer tank is used to store water for the remaining treatment steps and serves also as clean backwash water for sand filter.

Fourth unit is divided into 4A and 4B units, which both are granular activated carbon (GAC) filters. Their filtration process and backwash process is similar to sand filtration process. But unlike the sand filter, GAC A and GAC B purpose is to eliminate OMPs and is based on adsorption processes.

Following the GAC A and GAC B, a buffer tank water is used for the previous filter backwashes, and for the following unit five, UV disinfection. UV treatment is designed to inactivate pathogenic microorganisms, thereby safeguarding public health and preventing adverse impacts on aquatic ecosystems. However, this process does not remove organic micropollutants (OMPs) from the effluent and is therefore not considered further in this report.

A nanofiltration unit (**Figure 4**), separate from the pilot system, was tested independently. Rented from NX Filtration, the unit was evaluated over the course of a two months to assess its efficiency in removing OMPs, especially PFAS and pharmaceutical compounds. Effluent of a WWTP served as the feed water, and a membrane with a dNF40 size was employed.

Figure 4. Nanofiltration unit

Additionally, superfine powdered activated carbon (sPAC) was tested in combination with a PCMF system. For this setup, the filter media was replaced with finer cloth to enhance filtration. Effluent from a WWTP was pumped into a mixing tank, where both coagulant and sPAC were dosed proportionally to the water's total organic carbon (TOC) level. The recommended sPAC and coagulant dosages, as specified by the equipment provider based on prior experimental studies, were 0.6 g Fe/ g sPAC. During the testing period, the coagulant dosage was subsequently optimized according to turbidity measurements, with inlet values of approximately 30 NTU and outlet values of 1–3 NTU, to ensure effective coagulation performance.
After mixing, the sPAC-enriched water was directed to the PCMF unit, where a filtration process similar to that in unit one was carried out. Following filtration, the PCMF effluent was once again visibly clear.
The role of sPAC is comparable to that of GAC; however, due to its superfine particle size, sPAC has a significantly larger specific surface area than GAC. This characteristic theoretically enables it to adsorb a greater quantity of OMPs.

2.2.2. Operation of the pilot

The pilot plant is a controlled environment and is designed to automate the process. It is equipped with features to control water flow, level, turbidity with also the option to monitor water temperature, its pH level and electric conductance.

The pilot plant is controlled and monitored by HMI panel (**Figure 5**). Alternatively, the HMI is also accessible from the HMI webpage using computer web browser, which provides secure remote access to the pilot plant. The computer needs to be in the same network as HMI, alternatively there is also a possibility to use VPN.

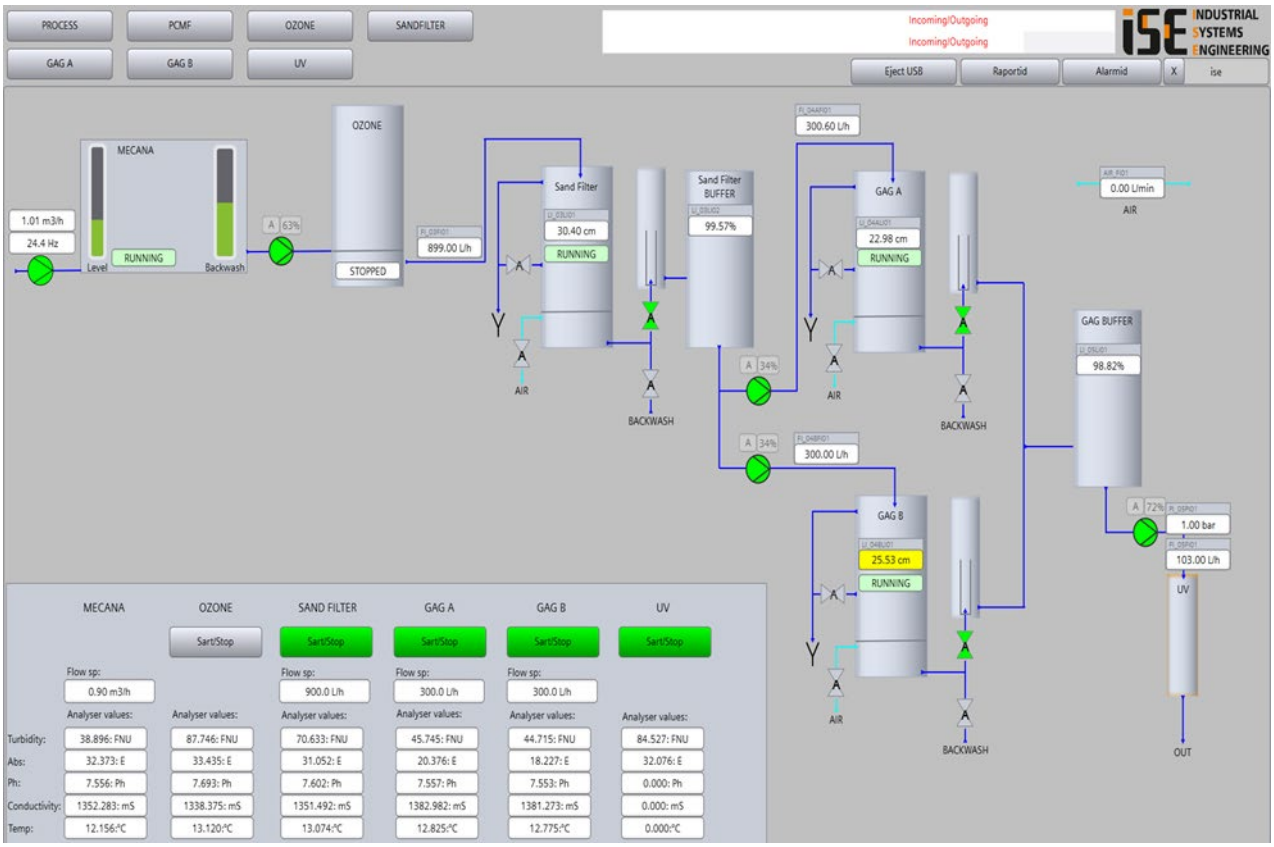

Figure 5. HMI display of the entire SCADA system process

Almost all the visual elements contain an interactive pop up with more details and parameters regarding the element. Additionally, the main process page provides a quick overview of the analyser data, allows specific processes to be turned on or off, and enables to set the parameters according to the need.

Furthermore, the on-site plant is designed for flexibility, featuring hoses with cam lock couplings that allow process steps to be easily connected or rearranged, and water pumps installed at the start of each treatment step. This adaptability enables more realistic pilot testing and planning, ensuring the system can be tailored to the specific requirements and future development plans of each participating wastewater treatment plant.

All equipment is installed in two high-cube sea containers (10 ft and 20 ft) to allow for easy transport and rapid commissioning at any water intake or wastewater treatment plant (**Figure 1**). Additionally, the containers are insulated to enable testing even in cold weather conditions.

To summarize, the key technological components of the pilot plant are listed below:

1) Mecana Pile Cloth Media Filter, type TF05-S-DUPLEX/A4 (PCMF)
   Set filter cloth type: Pile Fabric OptiFiber® PES-14
   Filter surface area 0.5 m^2
   max hydraulic capacity 5 m^3/h

Buffer tank after PCMF- Essential for maintaining continuous functionality of the following equipment while PCMF undergoes backwash cycle.

2) Ozonetech Rena Vivo A4 ozone system
   an ozone contact tank size 50 L
   max flow-through 250 L/min
   Ozone generator ICT 40 with nominal production of 40 g O_3/h
   Ozone concentration 135 g/Nm^3
   PSA technology-based oxygen generator- Onyx with flow of 6 L/min
   Nominal oxygen concentration 93 %

3) Sand filter (DMF)
   diameter 0.4 m
   surface area 0.126 m^2
   filter nozzles 36*0.3= 2.05 cm^2
   Filter media: 1.2-2.0 mm coarse sand in the bottom and top layer of Hydro-anthracite N with a grain size of 0.8-1.6 mm.
4) Granular activated carbon filters – 2 units (GAC A and GAC B)
   Filter media: Hydraffin AR 8x30
   surface area 0.126 m^2
   A backwash water storage tank
5) Saniray VX-245-6 ultraviolet (UV) lamp
   Maximum flow up to 0.7 m^3/h
   UV dose 400 J/m^2 at 60 % UV transmittance
   Wavelength 254 nm
6) Nanofiltration- separately tested from the effluent of WWTP
   direct Nanofiltration dNF 40 membrane
   cut off value 400 Daltons
7) sPAC (superfine activated carbon)- separately tested

2.1. Experimental setup

Tartu WWTP focused the studies on GAC filters, ozone oxidation, and eventually also on nanofiltration and sPAC, assuming that those technologies will create the most reduction in concentrations of organic micropollutants. GAC filtration would also be one of the easiest setups to create in actual conditions, although it requires extra space, like every other mentioned technology. The pilot containers were also used to evaluate the combined performance of all treatment technologies.
Although the initial plan to test all treatment steps in different combinations posed operational constraints, the plan was adjusted so that Tartu had the opportunity to assess each treatment step under varying effluent concentrations and different operational conditions throughout the study period.
Tartu WWTP divided the testing period (April-August 2024, and February 2025) into three periods with different combinations of technologies:

- Testing Period 1- Piloting with different setups
- Testing Period 2- Nanofiltration
- Testing Period 3- sPAC tests

2.2. Analytical methods

The performance of each treatment step was evaluated using an automatic analysis cell, which collected samples from each stage. The sampling frequency and duration are determined by the operator. In the case of Tartu, samples were taken from each treatment step every 60 minutes, with each sampling event lasting 1 minute. Additionally, random grab samples could be taken at any time by selecting the appropriate option from the HMI display.
The automatic analysis cell measured parameters such as turbidity, SAC 254, pH, conductivity, and temperature. **Figure 6** illustrates the analysis cell.

Figure 6. Automatic analysis cell for multipurpose samples at once

Manual valves were installed after each treatment stage to facilitate the collection of grab samples for laboratory analysis. These samples were analyzed both in Tartu WWTPs laboratory and in cross-border laboratories. During the testing period, WWTPs own laboratory measured a wide range of parameters, including: suspended solids, COD, BOD_7, TP, TN, and for the nanofiltration, also NAF, NH_4-N, NO_2-N, NO_3-N, PO_4-P, Color (Pt/Co), Ca, Mg, Cl, SO_4, Na, Fe, Mn, TDS, Hardness (mg-eq/L), alkalinity ($CaCO_3$).

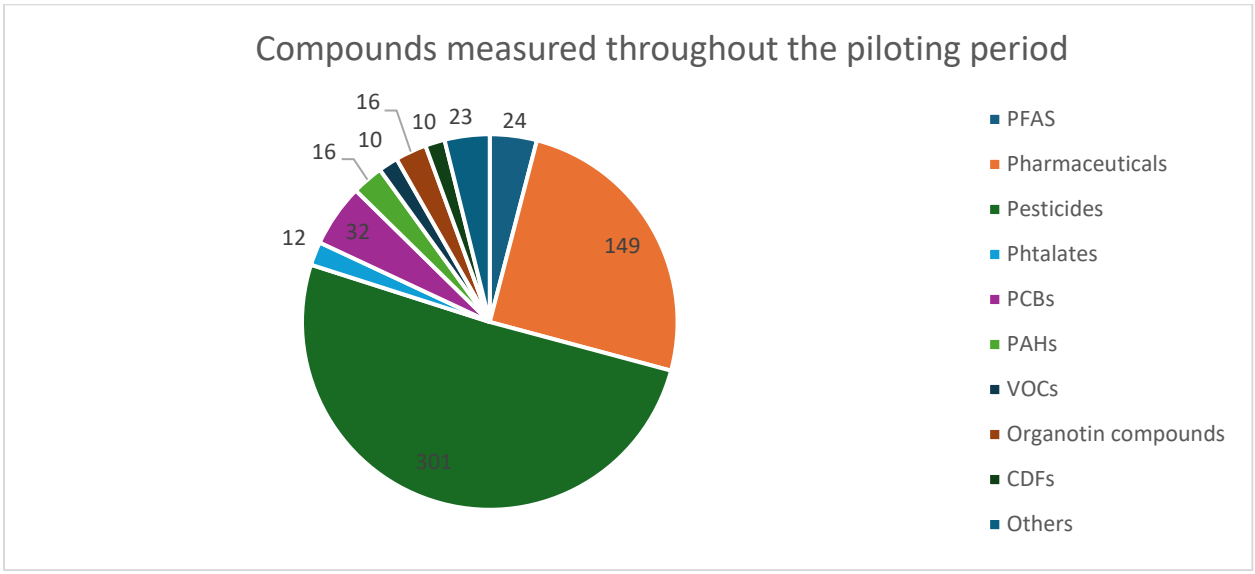

Figure 7. Measured compounds throughout the piloting period

For the analysis of organic micropollutants (OMPs), samples were sent to external laboratories across the border. Throughout the study, a total of 593 OMPs were analysed (all listed in **Appendix 1**), of which less than 20% were detected overall. Specifically, 33% of the measured PFAS compounds and 42% of the measured pharmaceutical compounds were found above the limit of quantification (LOQ). **Figure 7** shows the total number of analysed OMPs, organized according to their respective groups.

3. Results

The influent water of the pilot plant was the effluent water of Tartu WWTP. Effluent water of the WWTP was taken after the disc filters from the effluent chamber. Pilot plant consisted of two sea containers, where in first one, there is a pile cloth media filtration, and in the second container, ozonation, sand filter, GAC filters and UV disinfection.
The pilot test was carried out in four-month testing period starting from April 2024 and ending in August 2024. Automatic analyser data is saved throughout all the testing period if the pilot was functioning without disruptions, it was operated continuously.
Samples for PFAS, pharmaceuticals, and other micropollutants were collected twice per month and sent to specialized laboratories for analysis. Since measurements were costly during Tartu's research period, sampling focused on key points: the inlet, to establish baseline pollutant concentrations, and the effluent after different treatment stages, mainly including ozonation and GAC filtration.

3.1. Testing Period 1 – Piloting with different setups

Tartu, as the first pilot location, experienced minor malfunctions at the start, but most were resolved during operation. The focus was on keeping units running by replacing parts and adding a buffer tank, while also assessing how each technology performed under local conditions and addressing issues as they arose.
During the initial testing period, all treatment technologies were evaluated in sequence, with the two GAC filters operating in parallel. However, testing a completely different treatment line was not possible without modifying the pilot setup. Instead, we alternated the use of the ozone system, and GAC filters to examine their impact on overall removal efficiency.
During operation, the process parameters were typically as follows (flow rate Q, contact time CT):

- PCMF Q=1.5 m^3/h
- Ozone oxidation system, Q=0.8 m^3/h, CT=3.8 min
- Sand filter, Q=0.8 m^3/h, CT=7.6 min
- GAC A and GAC B, Q=0.25 m^3/h, CT= 24.24 min
- UV, Q=0.1 m^3/h

Ozone production was calculated followingly.If the nominal production of ozone generator is 40 g $\frac{\mathrm{O_3}}{\mathrm{h}}$, so 100 % and used $\mathrm{O_2}$ concentration is 97 %, then the operated O_3 capacity for 30% is:

$$40 \times 0.97 \times 0.3 = 11.64 \text{ g } \frac{\mathrm{O_3}}{\mathrm{h}}.$$

Ozone inlet concentration is:

$$11.64 \text{ g } \frac{\mathrm{O_3}}{\mathrm{h}} \div 0.8 \frac{m^3}{h} = 14.55 \text{ mg } \frac{\mathrm{O_3}}{L}.$$

Tartu WWTP effluent DOC value is 19 mg C/L. And therefore, ozone dose is:

$$14.55 \text{ mg } \frac{\mathrm{O_3}}{L} \div 19\ mg\ \frac{C}{L} = 0.77 \frac{g\ O_3}{g\ DOC}.$$

3.1.1. Removal of PFAS compounds

Out of 24 PFAS compounds, 8 PFAS compounds were found either from the effluent or formed/ released during the treatment processes. They include:

1) Short- chain PFAS (with lower than 7 carbon atoms): PFBA (C4), PFBS (C4), PFHxA (C6), PFHxS (C6), PFPeA (C5);
2) Long- chain PFAS (with higher than 6 carbon atoms): PFHpA (C7), PFOA (C8), PFOS (C8).

The following figures present the concentrations of individual PFAS compounds at each treatment step, starting with the shorter-chain compounds.

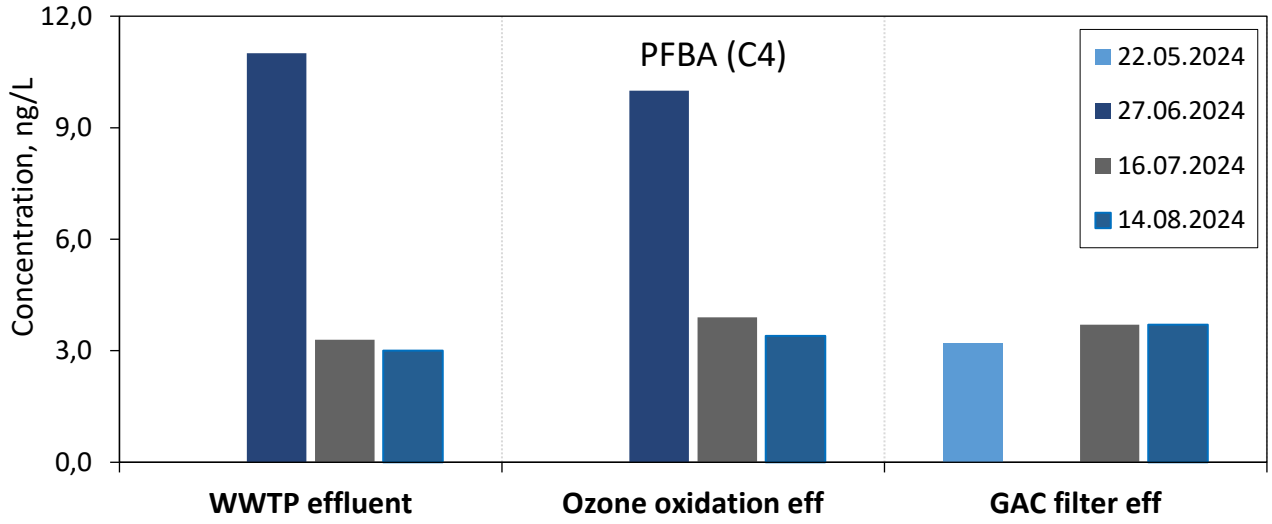

Figure 8. Reduction of PFBA (C4) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

PFBA, a short-chain PFAS, showed elevated concentrations in the WWTP effluent on June 27, 2024 (11 ng/L), which decreased slightly to 10 ng/L after ozone oxidation, corresponding to a 9.1% reduction. On other sampling dates, PFBA levels in the WWTP effluent were considerably lower, but increased following ozone treatment, 15 % on 16th of July and 12 % on 14th of August. In most cases, concentrations measured after the GAC filters were higher than those in the WWTP effluent, i.e., at the pilot plant inlet.

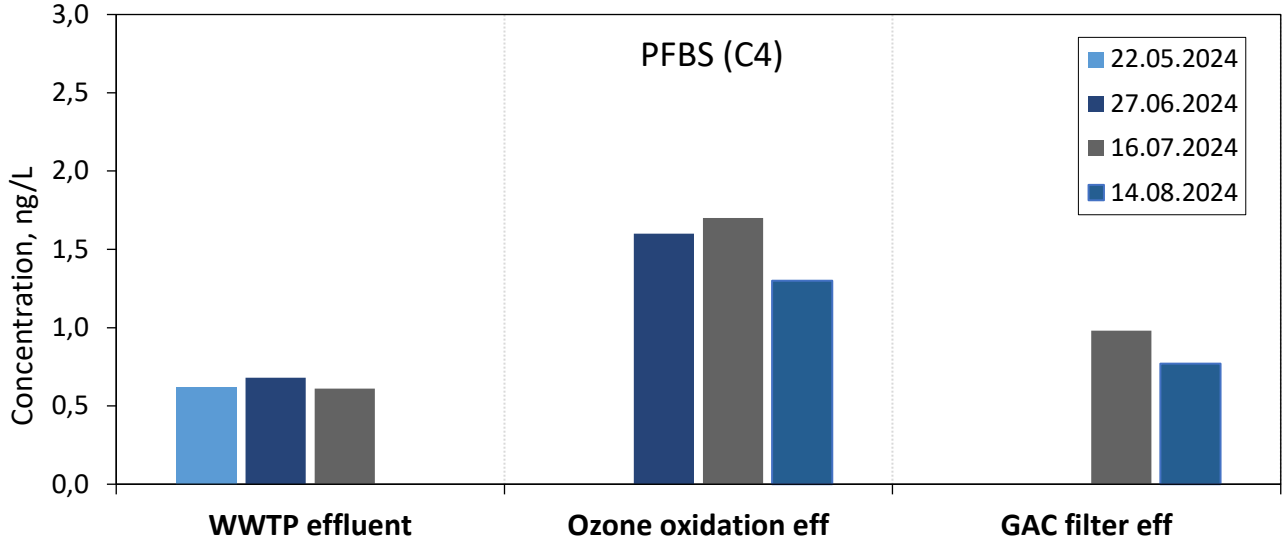

Figure 9. Reduction of PFBS (C4) after different stages of wastewater treatment. Specific color represents given date when grab sample was taken

PFBS concentrations in the WWTP effluent were substantially lower than those measured after ozone oxidation or GAC filtration. Increases following ozone oxidation were 58%, 64%, and 100% on June 27, July 16, and August

14, respectively. On May 22, when ozone oxidation was bypassed and the water was directed straight to the GAC filters, PFBS was completely removed (100% reduction).

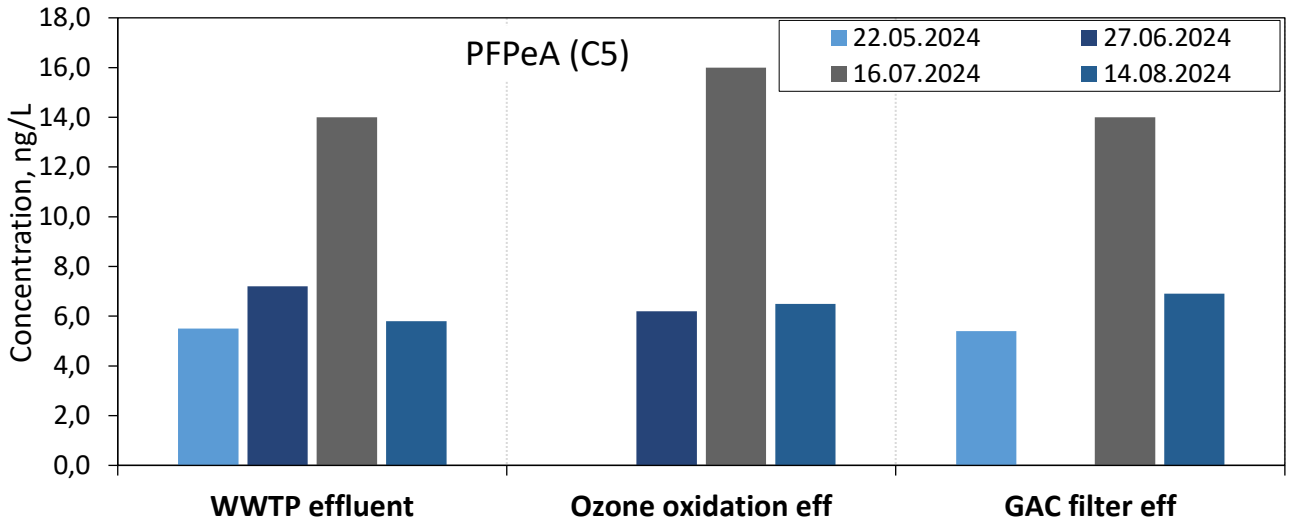

Figure 10. Reduction of PFPeA (C5) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

For PFPeA, no clear reduction was observed. Its concentrations fluctuated throughout the treatment process and ultimately remained within the same range as in the WWTP effluent, showing no consistent trend.

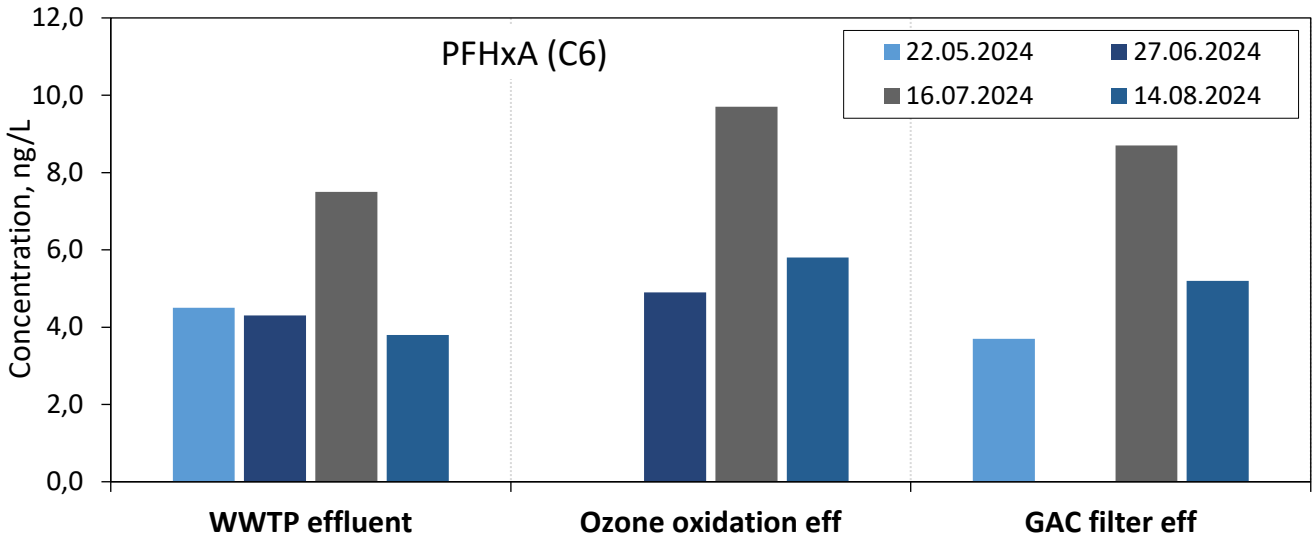

Figure 11. Reduction of PFHxA (C6) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

PFHxA exhibited a clear accumulation trend following ozone oxidation, with concentrations increasing by 12% on June 27, 23% on July 16, and 34% on August 14. In contrast, the only sampling date that bypassed ozone oxidation, May 22, 2024, showed consistent reductions, with concentration decreasing by 18% after GAC filtration.

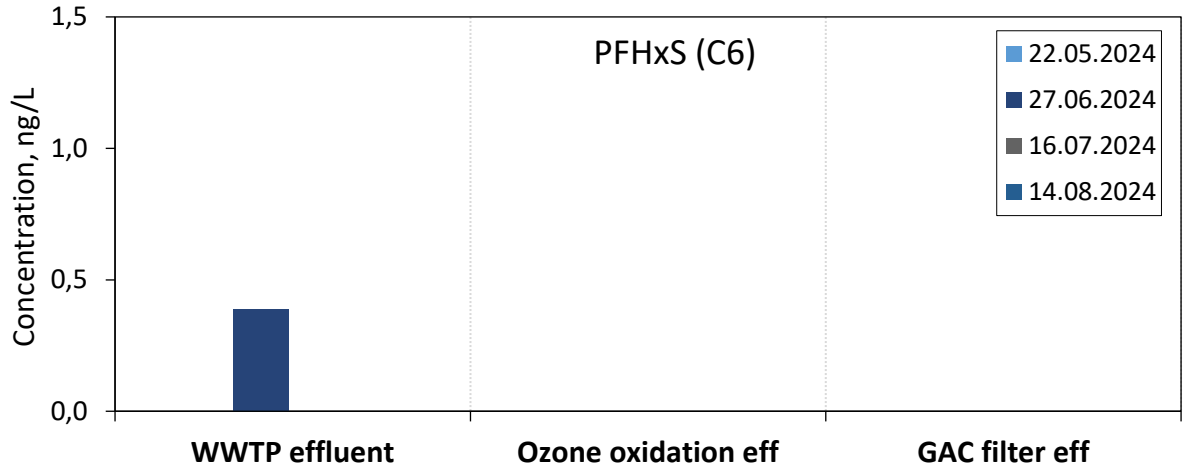

Figure 12. Reduction of PFHxS (C6) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

PFHxS was detected in only one of the five WWTP effluent samples, and its concentration was so low that subsequent treatment stages did not show levels above the LOQ.

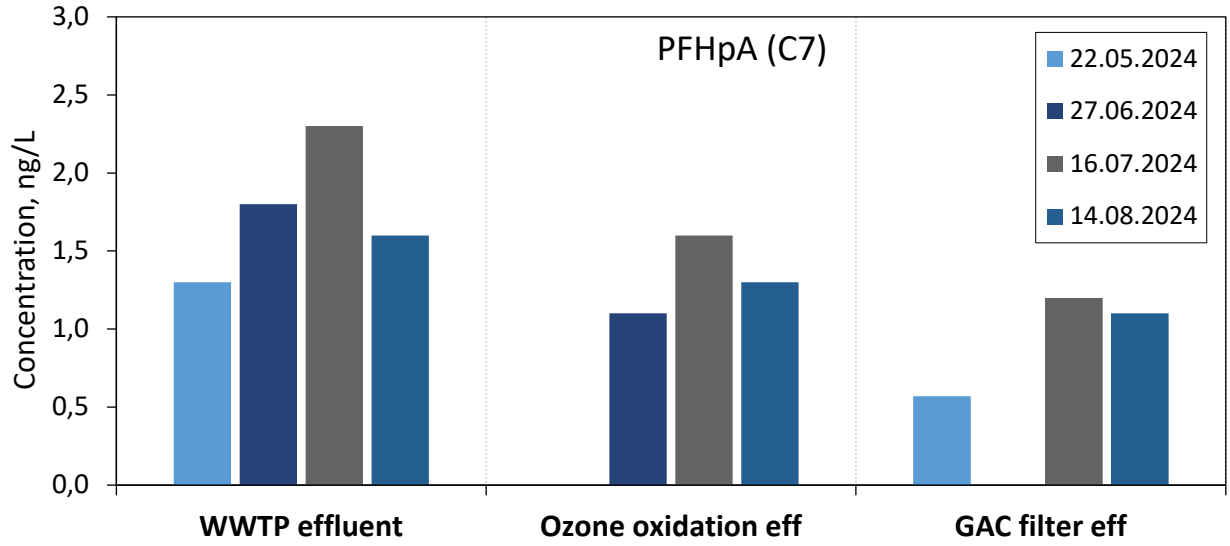

Figure 13. Reduction of PFHpA (C7) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

PFHpA concentrations decreased after each treatment step in all samples. Following ozone oxidation, reductions were observed as 39% on June 27, 30% on July 16, and 19% on August 14. In comparison, when ozone oxidation was bypassed, PFHpA decreased by 56%. For samples that underwent ozone oxidation prior to further treatment, the reduction rates were 25% on July 16 and 15% on August 14, 2024.

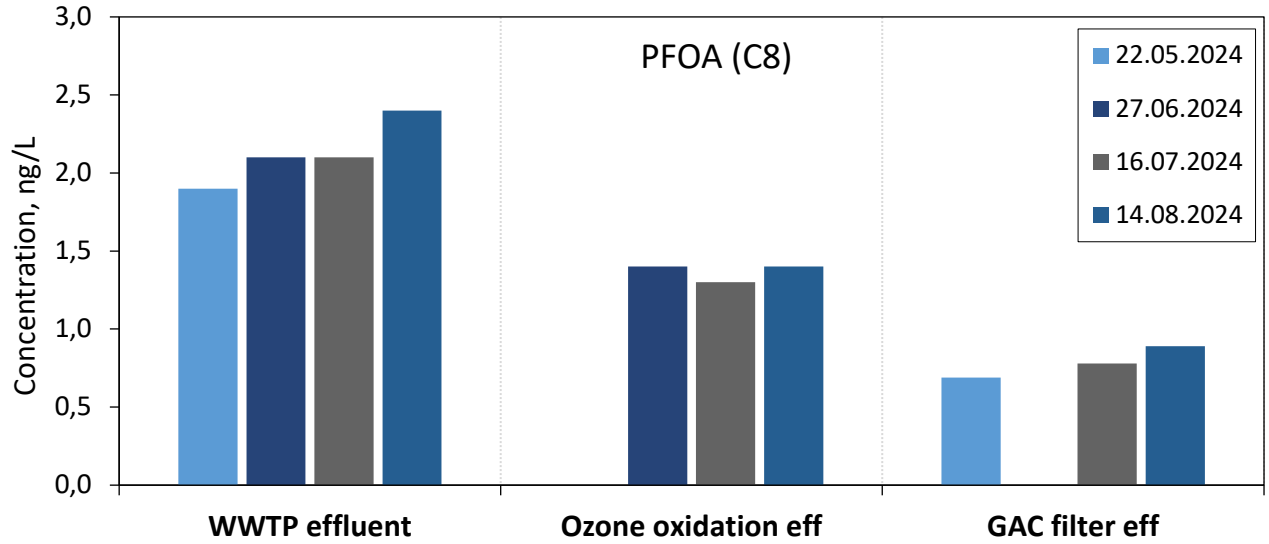

Figure 14. Reduction of PFOA (C8) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

PFOA shows a similar trend to PFHpA. Across all treatment steps, a decrease in concentrations is generally observed.

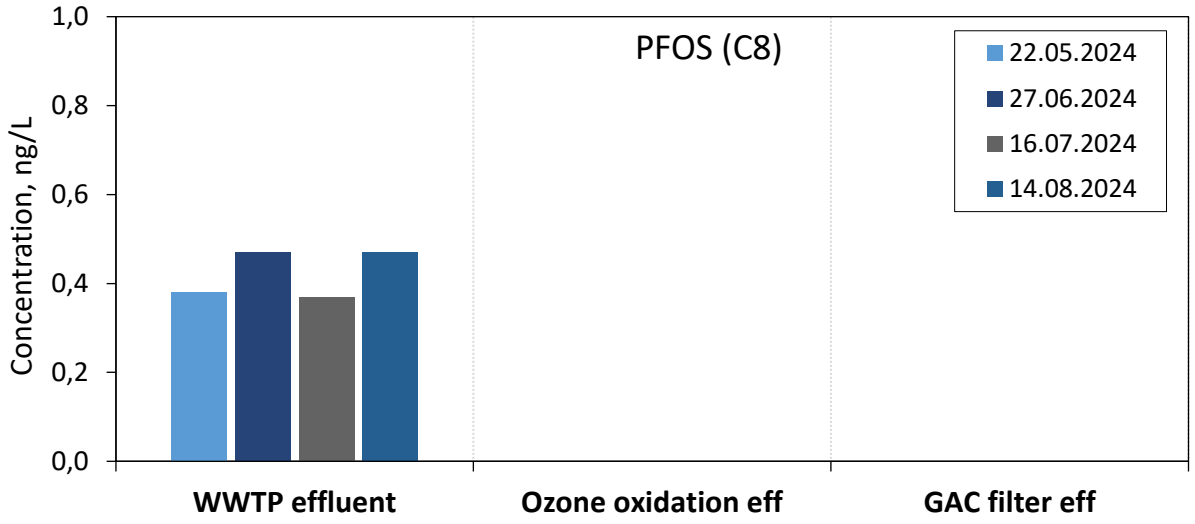

Figure 15. Reduction of PFOS (C8) after different stages of wastewater treatment. Specific colour represents given date when grab sample was taken

PFOS was the only detected long- chain PFAS, where already the first treatment steps showcased 100 % reduction in concentrations. As a long-chain PFAS, it may have degraded into shorter-chain PFAS compounds, which eliminates the long-chain fraction but does not remove PFAS or the broader class of organic micropollutants from the system. Another possibility is that PFOS concentrations in the WWTP effluent were already low, making it easier to eliminate them during treatment.

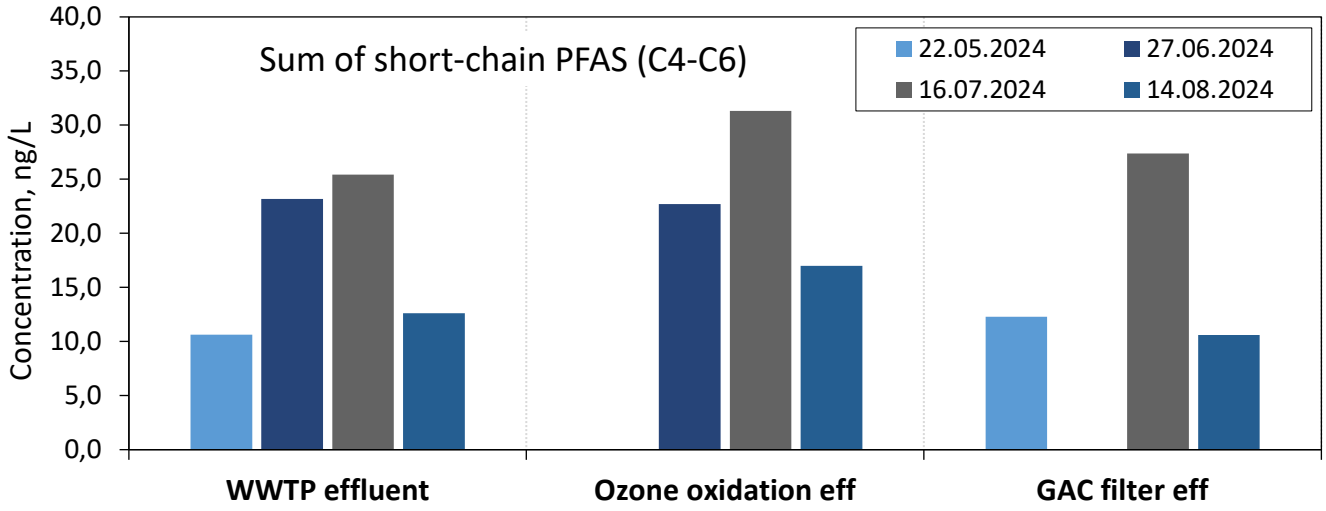

Figure 16. Sum of short-chain PFAS (C4-C6) concentrations

Figure 16. illustrates the removal efficiency of short-chain PFAS. The results indicate that ozone oxidation generally exhibited low efficiency, with some instances of negative removal, where concentrations exceeded those in the WWTP effluent. The summed concentrations of short-chain PFAS did not follow a consistent reduction pattern; in most cases, levels increased after ozone oxidation and subsequently decreased following GAC filtration.

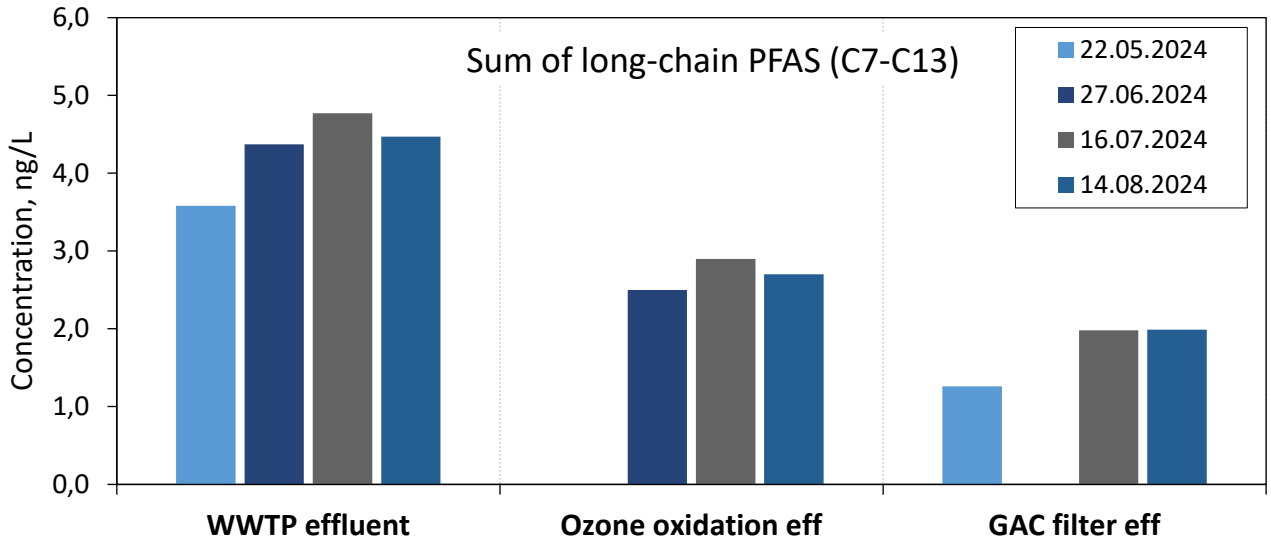

Figure 17. Sum of long- chain PFAS (C7-C13) compounds

In summary, long-chain PFAS compounds degraded more efficiently, with concentrations consistently decreasing at each treatment step. As shown on **Figure 17**, every stage contributed to the reduction of long-chain PFAS, with ozone oxidation and GAC filtration being particularly effective.

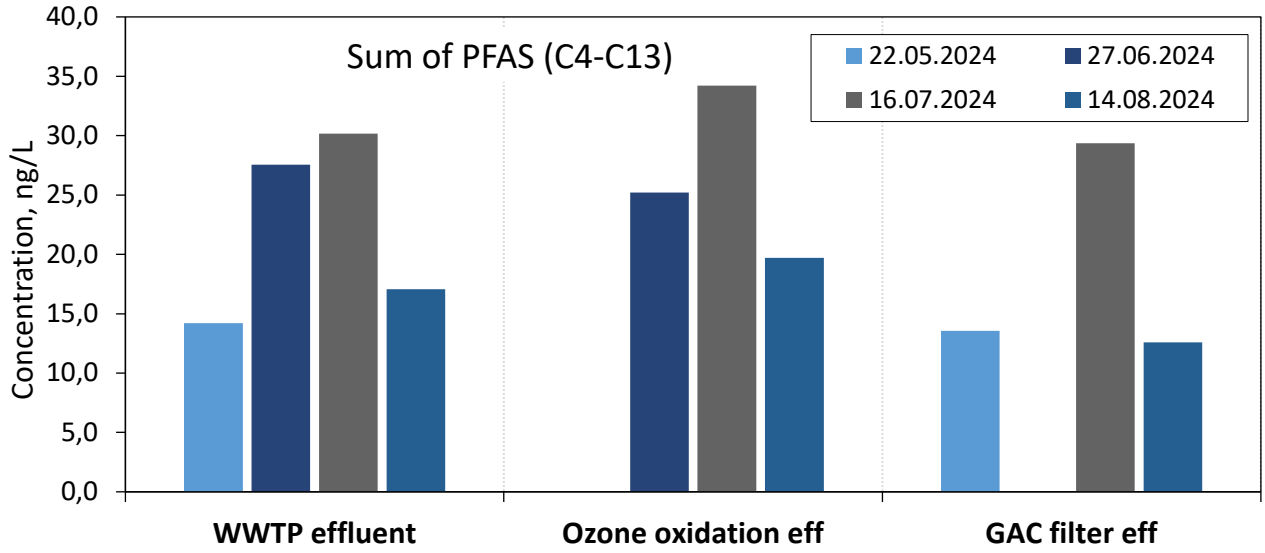

Figure 18. Sum of PFAS 24 compounds.

The summed concentrations of all measured PFAS in a single graph do not accurately reflect the effectiveness of ozone oxidation and indicate only minor reductions after GAC filtration. Instead, the graph primarily illustrates the behaviour of short-chain PFAS, whose limited or inconsistent removal obscures the overall treatment performance.

When summarizing **figures 16-18**, ozone oxidation can transform long-chain PFAS into shorter-chain PFAS, which may suggest some degree of effectiveness. However, PFAS are highly resistant due to their exceptional thermal and chemical stability, primarily resulting from the strength of the carbon–fluorine bond, one of the strongest in nature. Consequently, PFAS with strong carbon–fluorine bonds and electron-withdrawing functional groups (such as fluorine) remain largely resistant even to powerful oxidants such as ozone (Choe et al., 2022).

For a more accurate assessment, short- and long-chain PFAS should be evaluated separately to better understand their persistence and resistance to degradation across different treatment technologies.

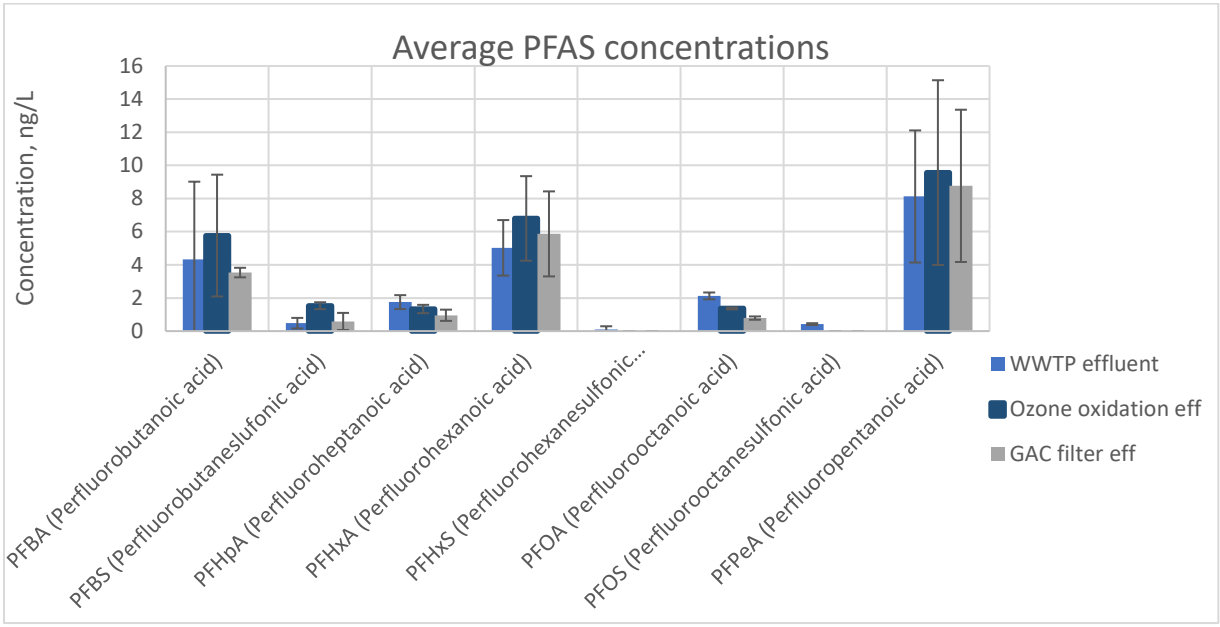

Figure 19. Average PFAS concentrations after each treatment step

Figure 19. represents average PFAS concentrations measured after each treatment step, with error bars representing the standard deviation of replicate measurements. In figure 19, higher concentrations in all

treatment steps are noted on short- chain PFAS compounds, such as PFPeA, PFHxA, and PFBA. Better removal trend draws out with the long- chain PFAS compounds.

Given the large number and structural diversity of PFAS, their concentrations are often normalized to PFOA equivalents using relative potency factors (RPF), allowing for integrated comparison and mixture risk assessment across the compound group.
The EU has proposed an updated surface water Environmental Quality Standard (EQS) for PFAS-24, which is 4.4 ng/L, expressed in PFOA equivalents. Specific water metric is used to compare the performance of the treatment technologies with the not-yet-finalized, but already applied, water matrix for surface water measurements, which has also been partially implemented for Estonian WWTP effluents.
The following figure presents all PFAS compounds detected in the WWTP effluent and compares their total concentrations with the EU limit value for the sum of PFAS.

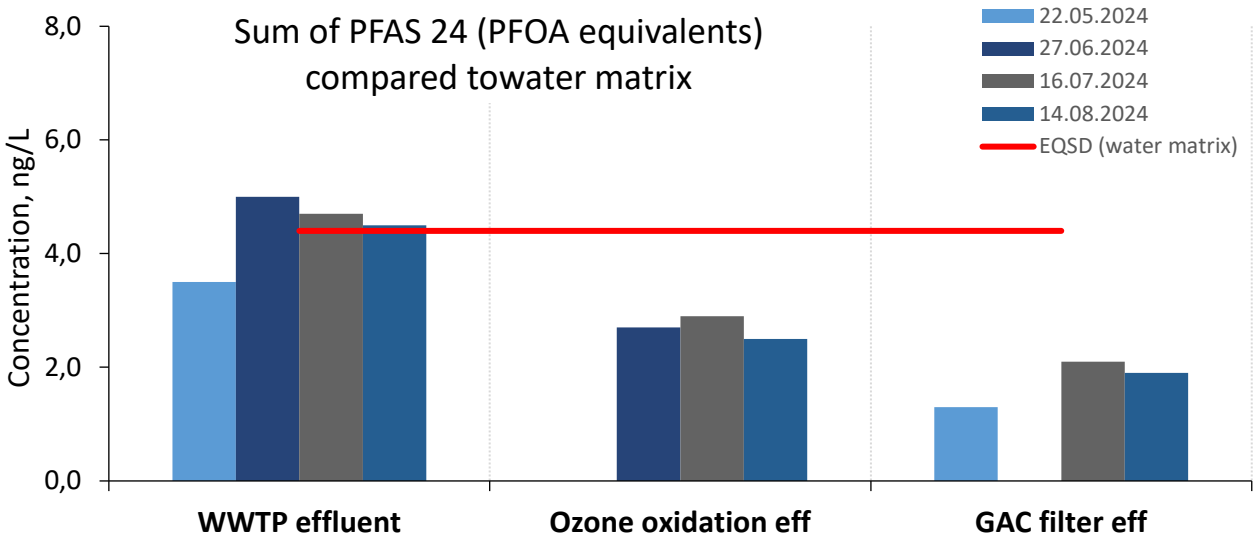

Figure 20. Sum of PFAS 24 (PFOA equivalents) compared to water matrix

Measured data indicates that the effluent of Tartu WWTP may slightly exceed the proposed water matrix value of 4.4 ng/L. Nevertheless, the treatment technologies demonstrate reductions in the sum of PFAS: on average 43% in the ozone oxidation effluent, 26% in the GAC filter effluent when preceded by ozonation, and 63% in the GAC filter effluent without prior ozonation.

3.1.2. Removal of other OMPs

In Tartu, the pilot was mainly tested between April and August 2024, several months before the recast Urban Wastewater Directive entered into force. During this period, pharmaceuticals and other OMPs were measured across a broad range to characterize the composition of Tartu's effluent. For clearer visualization, a selection of the more frequently occurring substances is presented here, including those that are now classified as Category 1 and 2 substances under the Directive (**Table 1**).

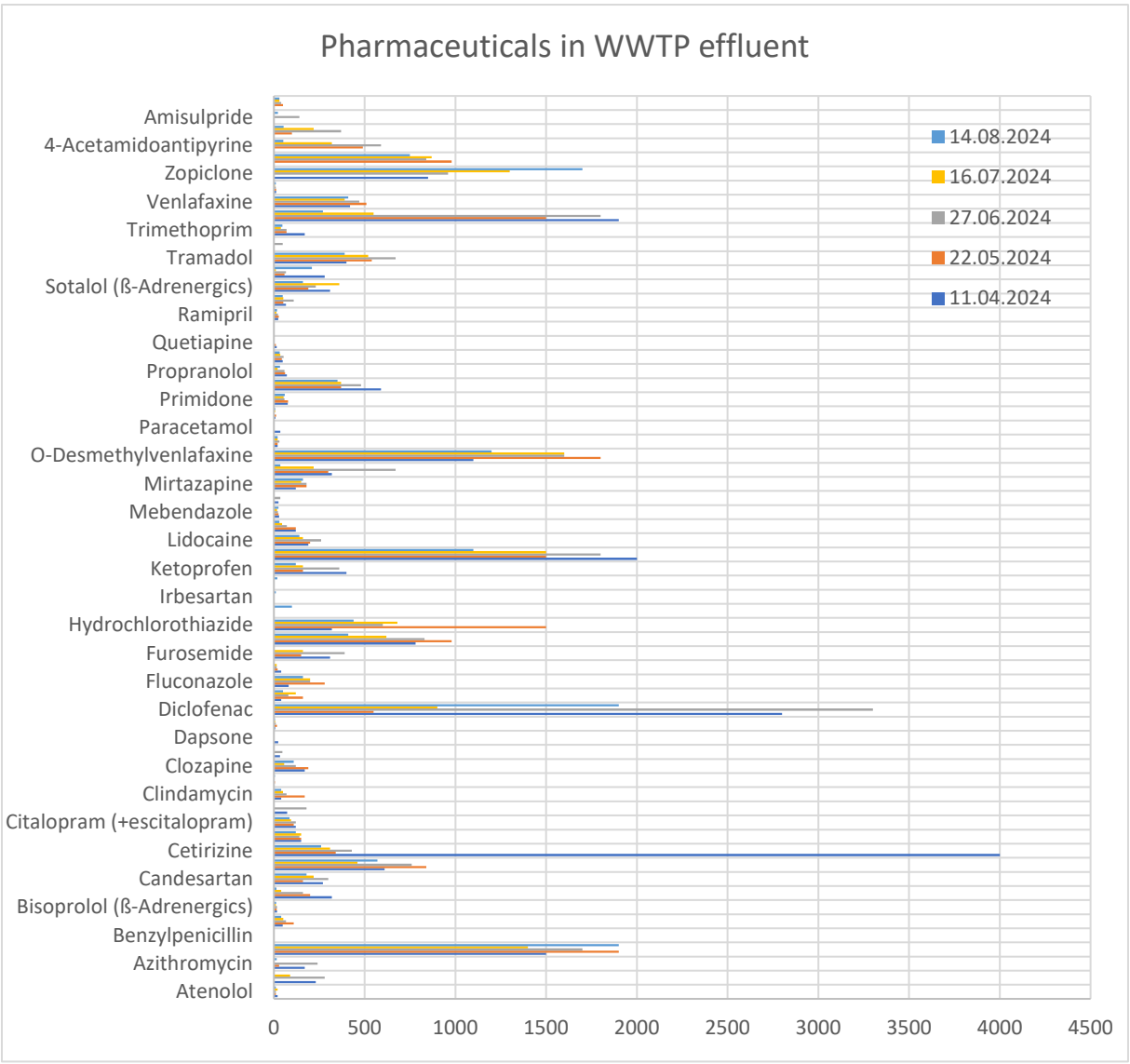

Figure 21. All the detected pharmaceuticals in the effluent of WWTP

Out of 149 pharmaceutical compounds analysed, 63 were detected during the testing period, corresponding to 42.3% of the total. The full list of analysed compounds is provided in **Appendix 1** under *Pharmaceuticals.*

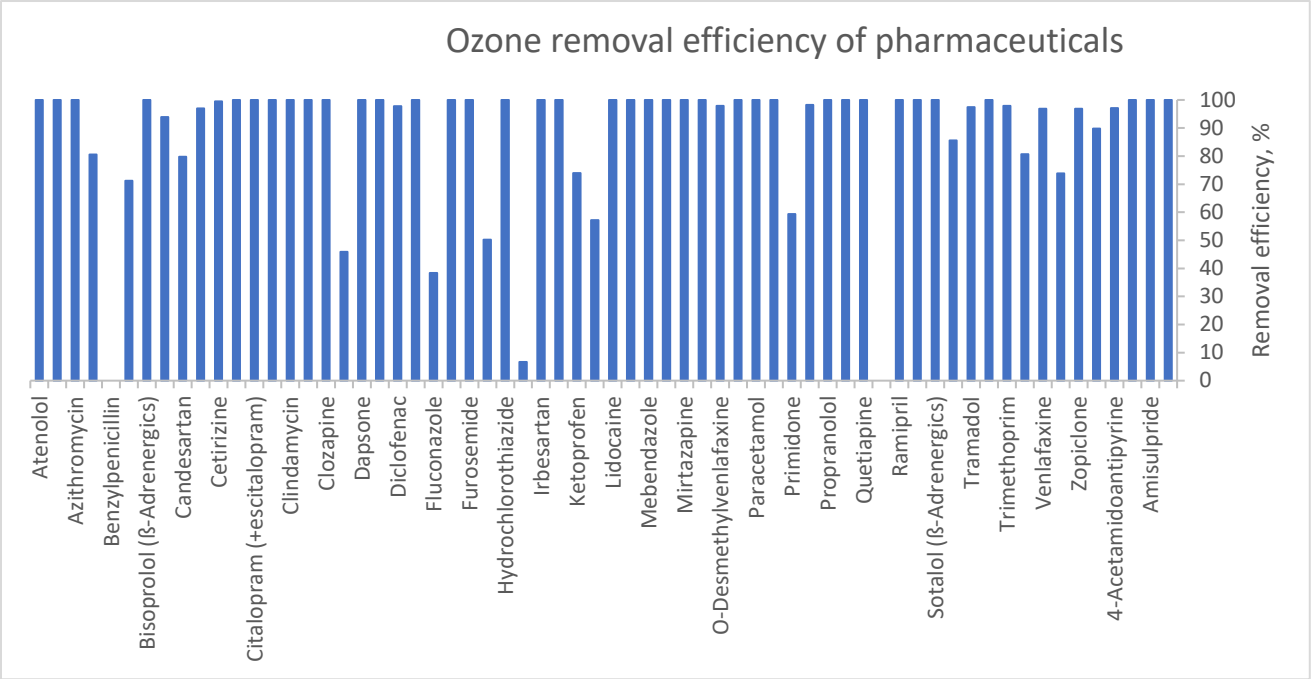

Figure 22. Average ozone removal efficiency of pharmaceuticals. Ozone dose of 0.77 g O_3/ g DOC, with the contact time of 3.8 min.

Despite the short contact time, applying the recommended ozone dose, considering the DOC of the WWTP effluent (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, 2022), resulted mostly in efficient removal of pharmaceuticals.

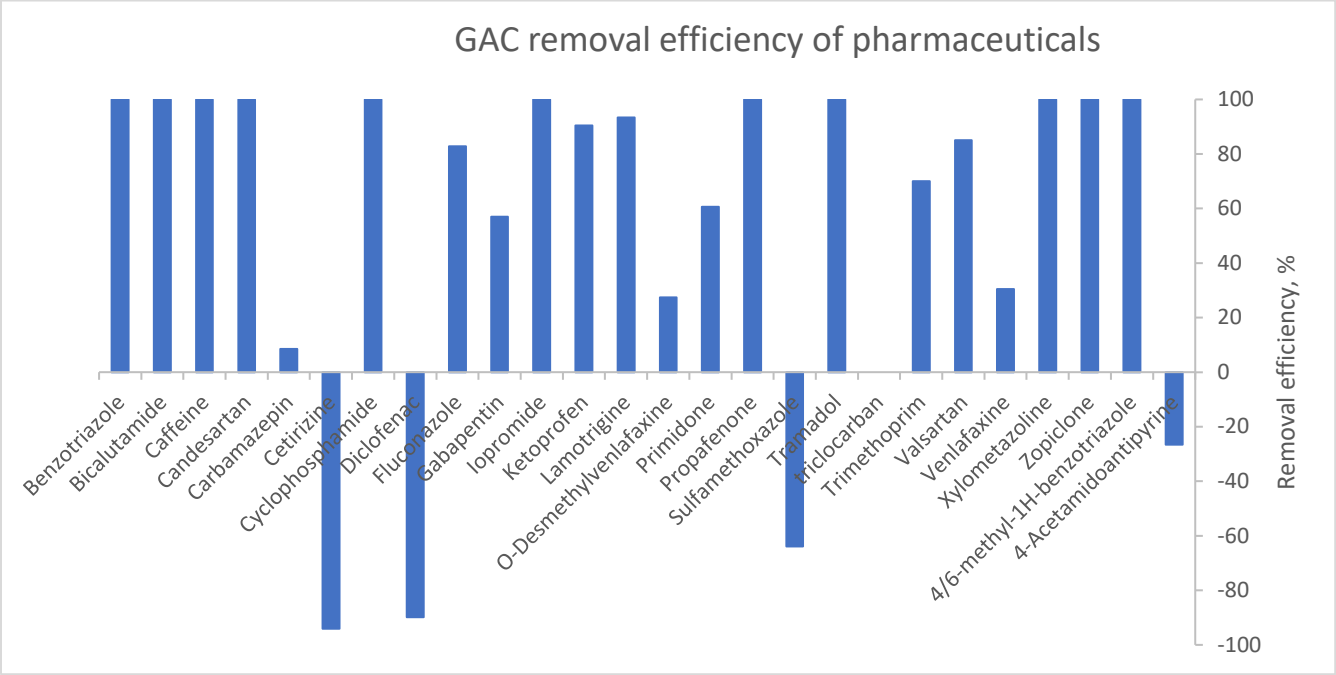

Figure 23. Average GAC removal efficiency of pharmaceuticals.

The graph illustrates the compounds remaining after ozone oxidation treatment. A negative removal efficiency indicates that, for example, Cetirizine accumulated in the GAC filter, resulting in an increased concentration in the filter effluent. Positive value shows how much of the compound has reduced in the effluent, 100 % means

that the effluent is clean from the compound. A positive value represents the reduction of the compound in the effluent, with 100% indicating complete removal.
With respect to pharmaceutical removal by the GAC filter, compounds such as Cetirizine, Diclofenac, Sulfamethoxazole, and 4-Acetamidoantipyrine exhibited strongly negative removal efficiencies. Although ozonation (**Figure 22**) eliminated at least 97% of these pharmaceuticals, they were subsequently released from the saturated GAC back into the effluent.

Table 1. Category 1 and 2 organic compound indicators listed in Urban Wastewater Directive (European Union, 2024, pp. 129–130).

Category 1	**CAS Number**
Amisulpride	71675-85-9
Carbamazepine	298-46-4
Citalopram	59729-33-8
Clarithromycin	81103-11-9
Diclofenac	15307-86-5
Hydrochlorothiazide	58-93-5
Metoprolol	37350-58-6
Venlafaxine	93413-69-5
Category 2	
Benzotriazole	95-14-7
Candesartan	139481-59-7
Irbesartan	138402-11-6
mixture of 4-Methylbenzotriazole and 5-methyl-benzotriazole	29878-31-7, 136-85-6 respectively

Table 1 lists the substances specified in Article 8 of the Directive, which define the requirements for quaternary treatment of discharges from urban wastewater treatment plants with capacity of 150,000 PE and above. These include Category 1 substances, which can be very easily treated, and Category 2 substances, which can be easily disposed of. Among these substances, at least six (with the number of Category 1 compounds being twice that of Category 2) should achieve a minimum of 80% removal from the effluent relative to their influent load (European Union, 2024).

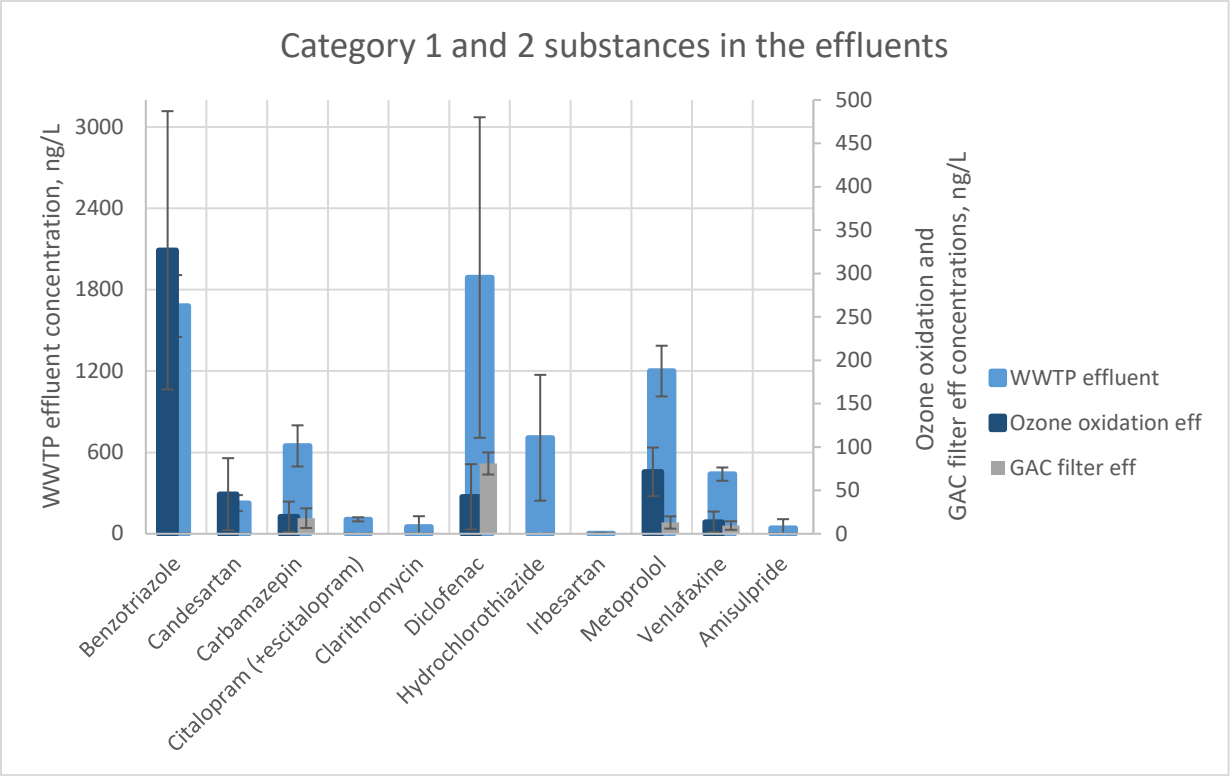

Figure 24. UWWD 2024/3019 Category 1 and 2 organic substances

The WWTP effluent underwent the following treatment sequence: PCMF → ozone oxidation → Sand filter → GAC A → UV disinfection. The data in **Figure 24** represent the average pharmaceutical concentrations across the treatment steps, which are detailed in the figure legend. When compared with the removal efficiency requirements set by the Directive, Diclofenac showed an average reduction of 98% after ozone oxidation. However, its concentration increased by 90% in the GAC filter effluent, likely due to the release of adsorbed organics after prolonged accumulation. Despite this fluctuation, the Directive's requirements are still fulfilled when assessed against the discharge concentrations in the WWTP effluent. In fact, all the indicators (**Table 1**) were reduced at least by 80 % by ozone oxidation treatment. Only after GAC, (additionally to Diclofenac) Carbamazepin reduced by 8 %, and Venlafaxine reduced by 30.5 %. Benzotriazole and Candesartan were removed 100 % after GAC treatment. Citalopram (+escitalopram), Clarithromycin, Hydrochlorothiazide, Irbesartan, and Amisulpride were completely removed (100 %) after the treatment with ozone oxidation.

3.2. Testing Period 2 – Nanofiltration

NX Filtration's advanced hollow-fibre membrane dNF40, with a molecular weight cut-off of 400 Daltons, was tested over a two-month period. During the initial phase, operational challenges emerged as the membrane experienced frequent fouling and fluctuating differential pressure (dP), which hindered consistent performance. After the chemical cleaning protocol was revised, membrane performance stabilized, enabling a reliable recovery rate of 85% (permeate). Once stable operation was achieved, grab samples were collected for analysis (NX Filtration, 2024).

3.2.1. Removal of PFAS compounds

During this two- month sampling period, 7 out of the 24 monitored PFAS compounds were detected. These can be categorized as follows:

- Short-chain PFAS: PFBA (C4), PFBS (C4), PFPeA (C5), PFHxA (C6);
- Long- chain PFAS: PFHpA (C7), PFOA (C8), PFOS (C8).

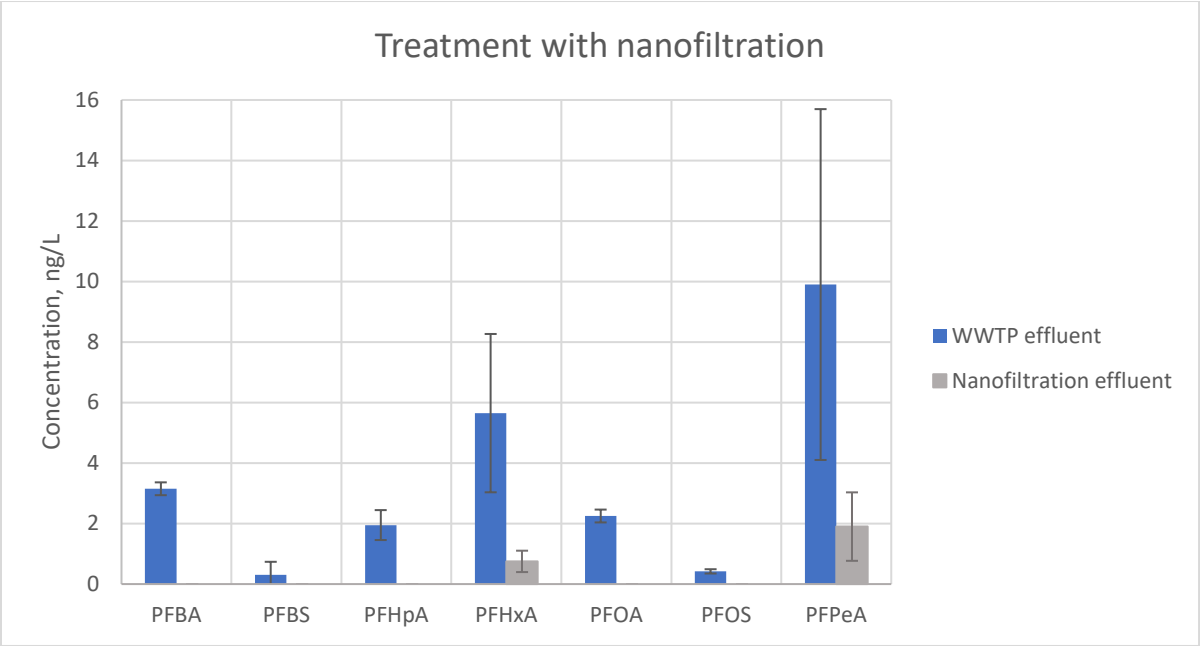

Figure 25. Treatment effect with nanofiltration.

Figure 25 presents combined data from two samples collected on 16 July and 14 August 2024. As the results were similar, their average concentrations are reported. The samples show that two short-chain PFAS compounds, PFHxA (C6) and PFPeA (C5), occurred at relatively high concentrations in the WWTP effluent. These compounds also exhibited the greatest variability, as reflected by their standard deviations. Following nanofiltration, all compounds were markedly reduced, ranging from an 81% decrease for PFPeA to concentrations below the LOQ (equivalent to 100% removal).

Although the nominal molecular weight cut-off of the applied nanofiltration membrane is 400 Da, this value represents an approximate threshold rather than a strict size barrier. In practice, molecules smaller than 400 Da may still be partially retained, particularly if they are charged. Since most PFAS are anionic at environmental pH, electrostatic repulsion between the negatively charged PFAS molecules and the typically negatively charged NF membrane surface contributes to their rejection. In addition, factors such as molecular shape, polarity, and hydration shell size further influence separation. This explains why even PFAS with molecular weights below 400 Da, such as PFHxA (314 g/mol) or PFPeA (264 g/mol), can be effectively retained to some extent by nanofiltration (NX Filtration, 2024).

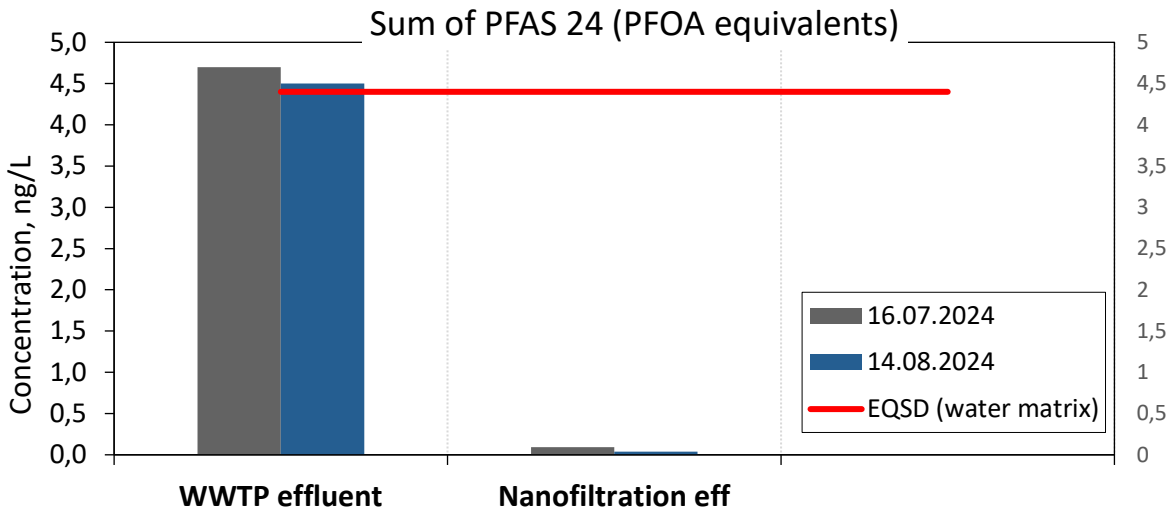

Figure 26. Efficiency of nanofiltration technology. PFAS concentrations are displayed in PFOA equivalents.

Figure 26 combines the two sampling periods, presenting the sum of 24 PFAS expressed in PFOA equivalents and comparing them with the water matrix. While concentrations in the WWTP effluent slightly exceeded the proposed EQS for the water matrix, treatment reduced the levels by 98% on July 16 and by 99% in August 14, 2024.

3.2.2. Removal of OMPs

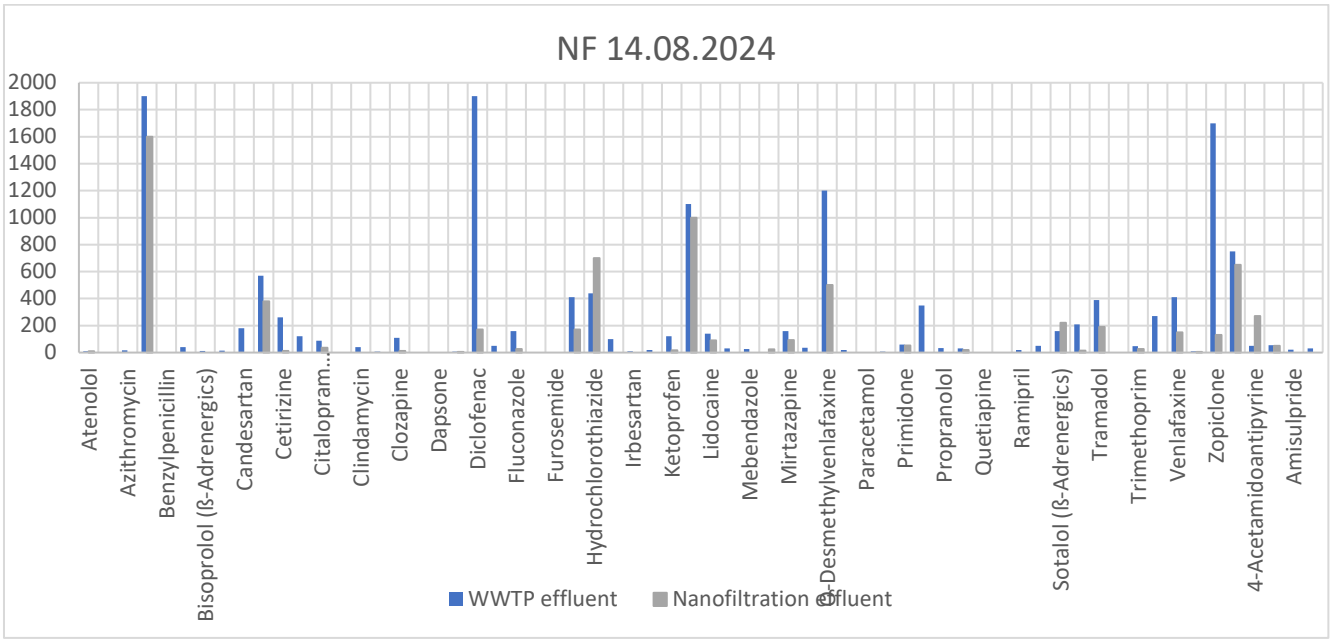

Figure 27. Example of the effect of nanofiltration on pharmaceuticals (14 August 2024)

Figure 27 illustrates data from 14 August 2024, showing the behaviour of other organic micropollutants, including pharmaceuticals with different charges and molecular weights. The DNF40 membrane exhibited similar performance for these micropollutants as it did for PFAS compounds.

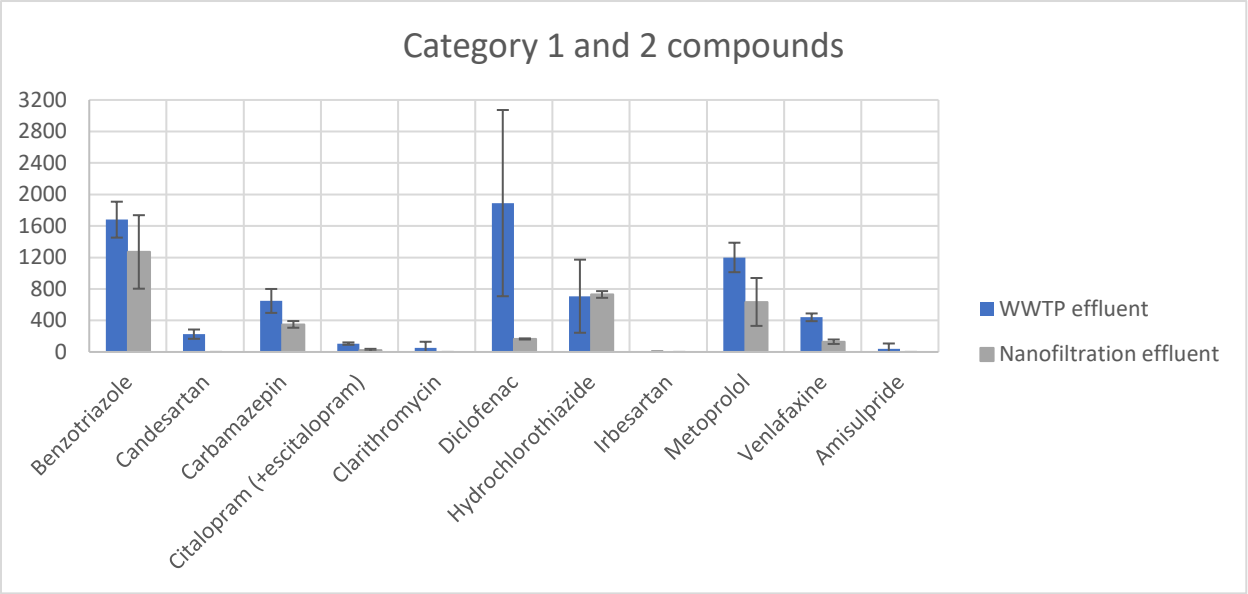

Figure 28. Category 1 and 2 compounds before and after the treatment with nanofiltration

Figure 28 shows the pharmaceuticals detected in the WWTP effluent. The graph indicates that compounds present at lower concentrations are generally effectively removed or reduced in the nanofiltration effluent. In contrast, compounds with higher initial concentrations tend to remain higher in the effluent, and in some cases, exceed the WWTP effluent levels, as observed for Hydrochlorothiazide (a neutral compound with a molecular weight of 297 g/mol).

Pharmaceuticals generally exhibit greater temporal and concentration variability than PFAS due to their diverse molecular structures, functional groups, and ionization behaviours, while PFAS typically maintain more stable and persistent concentrations in environmental and wastewater monitoring (Kurwadkar et al., 2022).In general, the concentrations of Category 1 and 2 compounds decreased after treatment. Nevertheless, nanofiltration occasionally resulted in slight increases in effluent concentrations. For instance, Hydrochlorothiazide (Category 1) increased by 3%, 4/6-methyl-1H-benzotriazole by 13%, and Sotalol (a β-adrenergic) by 2% in the nanofiltration effluent. The latter two are not included among the Category 1 and 2 indicator substances.

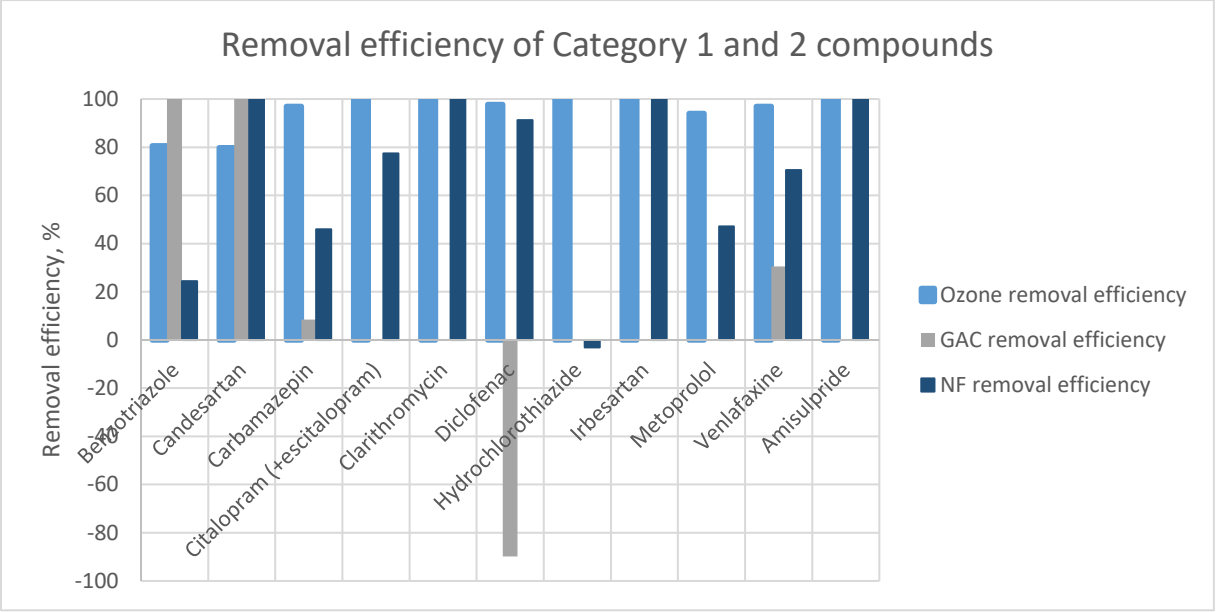

Figure 29. Summary of three treatment technologies for removing Category 1 and 2 pharmaceuticals

Figure 29 summarizes and compares three treatment technologies that have previously shown to be effective in specific report. The graph focuses on Category 1 and 2 substances listed in the new Urban Wastewater Directive. The mixture of 4-methylbenzotriazole and 5-methylbenzotriazole is excluded, as it was not measured at that time.

Diclofenac exhibited a notable increase in concentration after the GAC filter, despite being removed by 97% during ozone oxidation. This effect may occur when diclofenac or its transformation products (TPs), previously adsorbed onto the GAC, are later released (desorbed) as the filter becomes saturated or as conditions such as pH, ionic strength, or competitive adsorption change (Betsholtz et al., 2021; Chang et al., 2015). In most cases, however, the apparent removal efficiency across the GAC filter is negligible, since the majority of pharmaceuticals had already been degraded during the preceding ozonation step.

3.3. Testing Period 3 – sPAC tests

Superfine powdered activated carbon (sPAC) with coagulant iron (III)sulphate was dosed to the Mecana inlet chamber.

Mecana' s pile cloth media filter was changed to a finer cloth to catch the impurities with the finer sPAC from the system.

Testing period lasted for two weeks. As the water and dosing amounts were small, it´s operation became challenging due to small dosing amounts and too efficient pumps. Due to the short testing period and difficulties in always guaranteeing correct dosing, it is not adequate to make any concluding remarks. sPAC needs some further testing with bigger flow rates and higher sPAC dosing to assure proper functioning.

Nevertheless, samples were collected, and results are as follow.

3.3.1. Removal of PFAS compounds

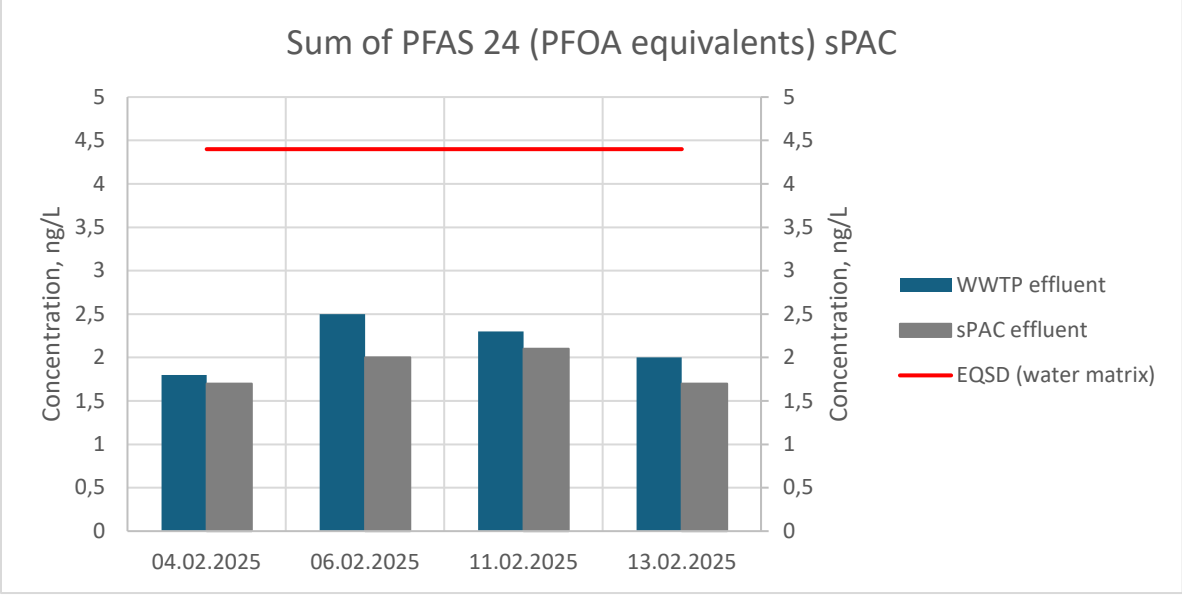

Figure 30. sPAC treatment efficiency. Concentrations are displayed in PFOA equivalents.

Samples were collected twice a week over a two-week period. In February 2025, the overall PFAS concentrations in the WWTP effluent were below the suggested EQS for the water matrix. During this period, 5 out of 24 monitored PFAS compounds were detected, categorized as follows:

- Short-chain PFAS: PFBA (C4), PFPeA (C5), PFHxA (C6)

- Long-chain PFAS: PFHpA (C7), PFOA (C8)

Despite the difficulties with small sPAC doses, the treatment reduced the overall PFAS levels, as illustrated in **Figure 30**.

3.3.2. Removal of OMPs

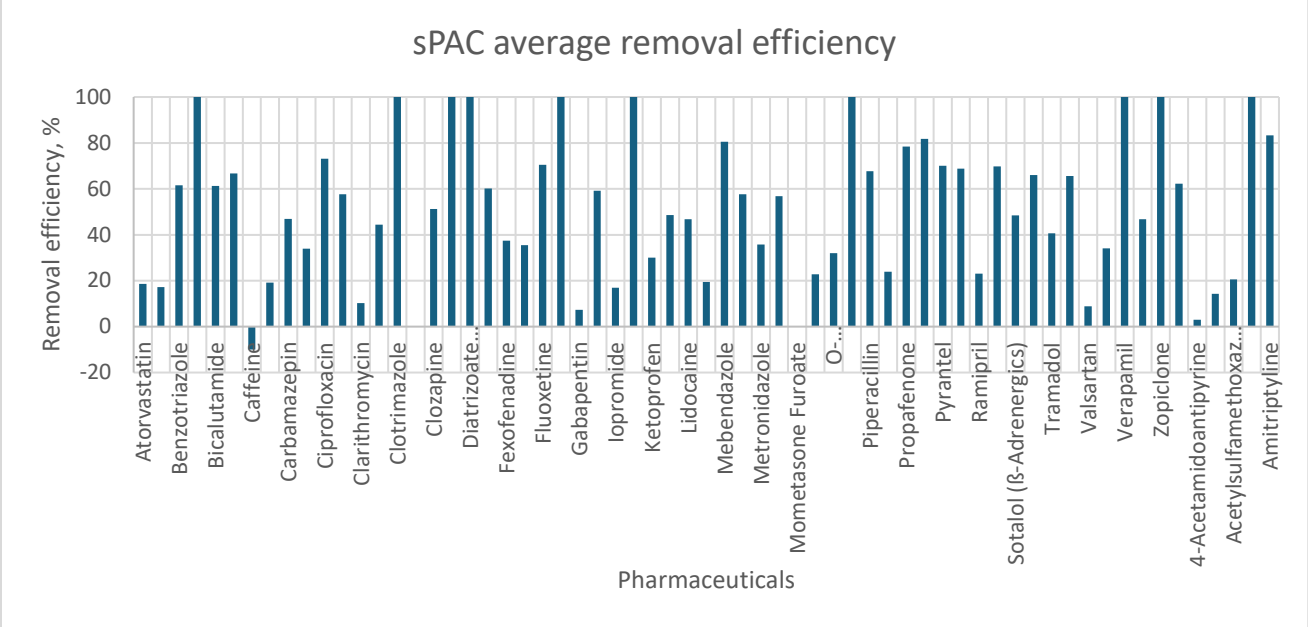

Figure 31. Average removal rate of pharmaceuticals by using nanofiltration

Figure 31 presents the average removal rate of OMPs. This was calculated by combining 4+4 samples of WWTP effluent and nanofiltration effluent (inlet and outlet separately) to obtain average concentrations, which were then used to determine removal efficiency. As illustrated in the graph, the removal efficiency of pharmaceutical compounds exhibits significant variability. This fluctuation can be attributed to several factors: competition for adsorption sites with natural organic matter (NOM), which can impede the adsorption of pharmaceuticals; the adsorption kinetics of pharmaceuticals, which may be slower than the available contact time; and the physicochemical properties of the pharmaceuticals, such as polarity and molecular weight, which influence their interaction with sPAC (Chang et al., 2015; Yilmaz et al., 2023; Zhang et al., 2025).

4. Conclusions

Tartu Waterworks Ltd. participated in the EU-co-funded Interreg Baltic Sea Region project EMPEREST (Eliminating Micropollutants from Effluents for Reuse Strategies). The project aimed to identify sustainable and efficient technologies for removing PFAS and other OMPs from WWTP effluent, in accordance with the requirements of the new Urban Wastewater Treatment Directive. To this end, Tartu built a pilot plant incorporating PCMF, ozone oxidation, sand filtration, two GAC filters, and UV disinfection, while also testing nanofiltration and sPAC.

The testing of PFAS, pharmaceuticals, and other organic micropollutants (OMPs) highlights the importance of identifying the compounds present in WWTP effluent and characterizing the effluent prior to selecting a treatment technology.

Ozonation, even with a short contact time but at a sufficient and recommended dose, achieved substantial reductions in pharmaceuticals and long-chain PFAS. Ozone oxidation transforms long-chain PFAS into short-chain PFAS but does not mineralize them completely.

GAC filters were effective in removing both PFAS and pharmaceuticals; however, smaller molecules can pass through the treatment more easily than larger compounds. Furthermore, GAC may release previously adsorbed compounds back into the effluent, occasionally resulting in increased concentrations.

Nanofiltration proved to be highly effective at removing PFAS compounds and pharmaceuticals to a significant extent. However, appropriate chemical cleaning protocols are essential to maintain stable operation and sustainable chemical consumption. With the recovery rate set at 85% (permeate), the remaining 15% is discharged as concentrate. This concentrate contains the removed OMPs, which, although eliminated from the permeate, are now retained in the waste stream. For the water company, this concentrate ultimately returns to the wastewater treatment plant (WWTP), where it accumulates either in the effluent or in the sludge. As a result, the issue is not eliminated from the waste stream. The management of this concentrated waste stream will be an important topic for future consideration, and WWTPs should take it into account when planning for larger-scale implementation.

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6. Appendixes

Appendix 1. Measured organic micropollutants grouped by category

PFAS compounds:

1) 6:2 FTOH (Fluorotelomer alcohol)
2) 8:2 FTOH (Fluorotelomer alcohol)
3) C6O4 ((Perfluoro([5-methoxy1,3dioxolan4yl]oxy)HAc)
4) DONA (Dodecafluoro-3H-4,8-dioxanon anoate)
5) HFPO-DA (GenX)
6) PFBA (Perfluorobutanoic acid)
7) PFBS (Perfluorobutaneslufonic acid)
8) PFDA (Perfluorodecanoic acid)
9) PFDoA (Perfluorododecanoic acid)
10) PFDS (Perflorodecanesulfonic acid)
11) PFHpA (Perfluoroheptanoic acid)
12) PFHpS (Perfluoroheptanesulfonic acid)
13) PFHxA (Perfluorohexanoic acid)
14) PFHxDA (Perfluorohexadecanoic acid)
15) PFHxS (Perfluorohexanesulfonic acid)
16) PFNA (Perfluorononanoic acid)
17) PFOA (Perfluorooctanoic acid)
18) PFODA (Perfluorooctadecanoic acid)
19) PFOS (Perfluorooctanesulfonic acid)
20) PFPeA (Perfluoropentanoic acid)
21) PFPeS (Perfluoropentane sulfonic acid)
22) PFTeDA (Perfluorotetradecanoic acid)
23) PFTrDA (Perfluorotridecanoic acid)
24) PFUdA (Perfluoroundecanoic acid)

Pharmaceuticals:

1) Ampicillin
2) Atenolol
3) Atorvastatin
4) Azathioprine
5) Azithromycin
6) Beclomethasone
7) Bendroflumethiazide
8) Benzathine benzylpenicillin G
9) Benzotriazole
10) Benzylpenicillin
11) Bezafibrate
12) Bicalutamide
13) Bisoprolol (ß-Adrenergics)
14) Bromocriptine
15) Budesonide
16) Buspirone
17) Caffeine
18) Candesartan

19) Carbamazepin
20) Carvedilol
21) Cetirizine
22) Ciprofloxacin
23) Citalopram (+escitalopram)
24) Clarithromycin
25) Clenbuterol
26) Clindamycin
27) CLOFIBRIC ACID
28) Clopidol (Meticlorpindol)
29) Clotrimazole
30) Cloxacillin
31) Clozapine
32) Crotamiton
33) Cyclophosphamide
34) Dapsone
35) Desloratadine
36) Dexmedetomidine
37) Diatrizoate (Amidotrizoate)
38) Diclofenac
39) Doxycycline
40) Enalapril
41) Enrofloxacin
42) Entacapone
43) Erythromycin
44) Febantel
45) Fenbendazole
46) Fexofenadine
47) Florfenicol
48) Flubendazole
49) Fluconazole
50) Fluoxetine
51) Flutamide
52) Fluvastatin
53) Fluvoxamine
54) Furosemide
55) Gabapentin
56) GEMFIBROZIL
57) Glibenclamide
58) Hydrochlorothiazide
59) Hydrocortisone
60) IBUPROFEN
61) Iopamidol
62) Iopromide
63) Ipratropium
64) Irbesartan
65) Irinotecan
66) Ivermectine
67) Ketoconazole
68) Ketoprofen

69) Lamotrigine
70) Levosimendan
71) Lidocaine
72) Loratadine
73) Losartan
74) Mebendazole
75) Meropenem
76) Metaflumizone (sum of E- and Z- isomers)
77) Methotrexate
78) methylprednisolone
79) Metoprolol
80) Metronidazole
81) Mianserin
82) Miconazole
83) Mirtazapine
84) Mometasone Furoate
85) NAPROXEN
86) N-Demethylerythromycin A
87) Nelfinavir
88) Nitenpyram
89) Norfloxacin
90) O-Desmethylvenlafaxine
91) Ofloxacin (+levofloxacin)
92) Oxazepam
93) Oxymetazoline
94) Oxytetracycline
95) Paracetamol
96) Paroxetine
97) Phenazon
98) Piperacillin
99) Praziquantel
100) Primidone
101) Propafenone
102) Propiphenazon
103) Propranolol
104) Pyrantel
105) Quetiapine
106) Raloxifene
107) Ramipril
108) Risperidone
109) Roxithromycin
110) Salbutamol
111) Salmeterol
112) Sertraline and norsertraline
113) Simvastatin
114) Sotalol (ß-Adrenergics)
115) Sulfadiazine
116) Sulfadimidine (Sulfamethazine)
117) Sulfadoxine
118) Sulfaguanidine

119) Sulfamerazine
120) Sulfamethizole
121) Sulfamethoxazole
122) Sulfathiazole
123) Tamoxifen
124) Terbutalin
125) Tetraconazole
126) Tetracycline
127) Toremifene
128) Tramadol
129) triclocarban
130) Trimethoprim
131) Valsartan
132) Venlafaxine
133) Verapamil
134) Warfarin
135) Xylometazoline
136) Zolpidem
137) Zopiclone
138) Diltiazem
139) 4/6-methyl-1H-benzotriazole
140) 4-Acetamidoantipyrine
141) 4-Formylaminoantipyrine (Formyl-AAP)
142) Acetanilid
143) Acetylsulfamethoxazole
144) Amiloride
145) Amiodarone
146) Amisulpride
147) Amitriptyline
148) Amlodipine
149) Amoxicilline

Pesticides:

1) 1-(3,4-Dichlorophenyl)urea
2) 2,6-dichlorobenzamide (BAM)
3) 2-amino-N-(isopropyl)benzamide
4) 2-hydroxyatrazine
5) 2-Chloro-2.6-diethylacetanilide
6) Aclonifen
7) Alachlor
8) Aldicarb
9) Aldicarb sulfone
10) Ametryn
11) Amidosulfuron
12) Acetamiprid
13) Acetochlor
14) Acibenzolar-S-methyl
15) Atraton
16) Atrazine
17) Azinphos-methyl

18) Azinphos-ethyl
19) Azoxystrobin
20) BDMC
21) Benalaxyl
22) Bendiocarb
23) Bentazone methyl
24) Bifenox
25) Bitertanol
26) Boscalid
27) Bromacil
28) Bromophos-ethyl
29) DEET
30) Difenoconazole
31) Des-ethyl atrazine (DEA)
32) Des-isopropyl atrazine (DIA)
33) Desmetryn
34) Diazinon
35) Diethofencarb
36) Difenacoum
37) Difenoxuron
38) Diflubenzuron
39) Diflufenican
40) Dichlofenthion
41) Dichlormid
42) Dichlorvos
43) Dicrotophos
44) Dimefuron
45) Dimethachlor
46) Dimethenamid
47) Dimethoate
48) Dimethomorph
49) Diuron
50) Diuron desmethyl (DCPMU)
51) Epoxiconazole
52) EPTC
53) Ethiofencarb
54) Ethion
55) Ethofumesate
56) Ethoprophos
57) Fenamiphos
58) Fenarimol
59) Fenhexamid
60) Fenoxaprop
61) Fenoxycarb
62) Fenpropidin
63) Fenpropimorph
64) Fensulfothion
65) Fenuron
66) Fipronil
67) Florasulam

68) Fluazifop
69) Fluazifop-butyl (isomers)
70) Flusilazole
71) Flutolanil
72) Fonofos
73) Phorate
74) Foramsulfuron
75) Phosalone
76) Phosphamidon
77) Phosmet
78) Furathiocarb
79) Haloxyfop
80) Haloxyfop-methyl (isomers)
81) Hexaconazole
82) Hexazinone
83) Hexythiazox
84) Imazalil
85) Imazamethabenz-methyl
86) Imazamox
87) Imazethapyr
88) Imidacloprid
89) Indoxacarb
90) Iprodione
91) Iprovalicarb
92) Isoproturon
93) Isoproturon-desmethyl
94) Isoproturon-monodesmethyl
95) Isopyrazam
96) Cadusafos
97) Carbaryl
98) Carbendazim
99) Carbetamide
100) Carbofuran
101) Carbofuran-3-hydroxy
102) Carboxin
103) Carfentrazone-ethyl
104) Clodinafop
105) Clomazone
106) Clomeprop
107) Chloridazon-desphenyl
108) Chlorotoluron
109) Chlorbromuron
110) Chlorfenvinphos
111) Chloridazon
112) Chloroxuron
113) Chlorotoluron-desmethyl
114) Chlorpropham
115) Chlorpyrifos
116) Chlorpyrifos-methyl
117) Chlorsulfuron

118) Clothianidin
119) Kresoxim-methyl
120) Crimidine
121) Coumaphos
122) Quinclorac
123) Quinmerac
124) Quinoxyfen
125) Quizalofop
126) Lenacil
127) Linuron
128) Malaoxon
129) Malathion
130) Mandipropamid
131) Mefenpyr-diethyl
132) Mecarbam
133) Mesosulfuron-methyl
134) Mesotrione
135) Methabenzthiazuron
136) Metalaxyl (isomers)
137) Methamidophos
138) Metamitron
139) Metazachlor
140) Methidathion
141) Methiocarb
142) Metconazole
143) Metobromuron
144) Methoxyfenozide
145) Metoxuron
146) Metolachlor (isomers)
147) Methomyl
148) Metribuzin
149) Metribuzin-desamino
150) Metsulfuron-methyl
151) Molinate
152) Monocrotophos
153) Monolinuron
154) Monuron
155) Napropamide
156) Naptalam
157) Neburon
158) Nicosulfuron
159) Nuarimol
160) Oxadixyl
161) Oxamyl
162) Omethoate
163) Paclobutrazol
164) Paraoxon-ethyl
165) Paraoxon-methyl
166) Parathion-ethyl
167) Pendimethalin

168) Penconazole
169) Pencycuron
170) Picloram
171) Picoxystrobin
172) Pirimiphos-ethyl
173) Pirimiphos-methyl
174) Pirimicarb
175) Pretilachlor
176) Primisulfuron-methyl
177) Prodiamine
178) Propham
179) Profenofos
180) Prochloraz
181) Promecarb
182) Prometon
183) Prometryn
184) Propachlor
185) Propaquizafop
186) Propamocarb
187) Propanil
188) Propazine
189) Propiconazole
190) Propoxycarbazone-sodium
191) Propoxur
192) Propyzamide
193) Prosulfocarb
194) Prothioconazole
195) Pyribenzoxim
196) Pyrimethanil
197) Pyriproxifen
198) Rimsulfuron
199) Sebuthylazine
200) Secbumeton
201) Sethoxydim
202) Simazine
203) Simazine-2-hydroxy
204) Simetryn
205) Spiroxamine
206) Sulfosulfuron
207) Cyanazine
208) Cybutryne (Irgarol)
209) Cymoxanil
210) Cyprazine
211) Cyprodinil
212) Cyproconazole
213) Cyromazine
214) Tebuconazole
215) Tebuthiuron
216) Teflubenzuron
217) Terbutryn

218) Terbuthylazine-hydroxy
219) Terbuthylazine
220) Terbuthylazine-desethyl
221) Terbuthylazine-desethyl-2-hydroxy
222) Thiabendazole
223) Thiamethoxam
224) Thifensulfuron-methyl
225) Thiobencarb
226) Thiophanate-methyl
227) Triadimefon
228) Triadimenol
229) Tri-allate
230) Triasulfuron
231) Triazophos
232) Tribenuron-methyl
233) Trifloxysulfuron-sodium
234) Triflusulfuron-methyl
235) Triforine
236) Tricyclazole
237) Triticonazole
238) Aldrin
239) 2,4-D
240) 2,4 D 2-EHE
241) α-endosulfan
242) β-Endosulfan
243) endosulfan sulphate
244) endrin
245) dieldrine
246) dicofol
247) α-chlordane
248) gamma-chlordane
249) Oxychlordane
250) Heptachlor
251) Heptachlor-exo-epoxide
252) Heptachlor-endo-epoxide
253) Mirex
254) Isobenzan
255) Isodrine
256) o,p'-DDD
257) o,p'-DDE
258) o,p'-DDT
259) methoxychlor
260) α-Hexachlorocyclohexane
261) β-hexachlorocyclohexane
262) delta-Hexachlorocyclohexane
263) epsilon-hexachlorocyclohexane
264) gamma-hexachlorocyclohexane
265) bifenthrin
266) deltamethrin
267) esfenvalerate

268) fenpropathrin
269) fenvalerate
270) Lambda-cyhalothrin
271) Permethrin
272) Promethrin
273) Cyfluthrin
274) cypermethrin (mixture of isomers)
275) fenitrothion
276) thiacloprid
277) isoprocarb
278) amethryn
279) AMPA
280) Biphenox
281) Diclobenil
282) dichlorprop-P
283) dimethenamid-P
284) fluroxypyr
285) clopyralid
286) kvintosen
287) MCPA
288) Metabenstiasuron
289) Metakrifoss
290) Nikosulfuron
291) Pinoxaden
292) Propam
293) terbutryn
294) triallate
295) trifluralin
296) tritosulfuron
297) glyphosate
298) chlormequat chloride
299) mepiquat chloride
300) propiconazole-destio
301) cloroxyron

PCBs:

1) PCB 114
2) PCB 118
3) PCB 123
4) PCB 126
5) PCB 156
6) PCB 157
7) PCB 167
8) PCB 169
9) PCB 170
10) PCB 180
11) PCB 189
12) PCB 77
13) PCB 81
14) PCB-101
15) PCB-105
16) PCB-114
17) PCB-118
18) PCB-123
19) PCB-126
20) PCB-138
21) PCB-153
22) PCB-156
23) PCB-157
24) PCB-167
25) PCB-169
26) PCB-180
27) PCB-189
28) PCB-194

29) PCB-28
30) PCB-52
31) PCB-77
32) PCB-81

Phtalates:

1) BBP (benzyl butyl phthalate)
2) DEP (diethyl phthalate)
3) diethylhexyl phthalate
4) DIBP (diisobutyl phthalate)
5) DOP (di-n-octyl phthalate)
6) DPP (di-n-propyl phthalate)
7) di-pentyl phthalate
8) DMP (dimethyl phthalate)
9) DBP (dibutyl phthalate)
10) DEHP (di-2-ethylhexaphthalate)
11) DUP (diundecyl phthalate)
12) DCP (dicyclohexyl phthalate)

PAHs:

1) Naphtalene
2) Anthracene
3) benzo(a)anthracene
4) Azenaphthene
5) Azenaphthylene
6) benzo(a)pyrene
7) benzo(a)pyrene
8) benzo(b)fluoranthene
9) benzo(k)fluoranthene
10) benzo(g,h,i)perylene
11) dibenzo(a,h)anthracene
12) fluoranthene
13) fluorene
14) indeno(1,2,3-cd)pyrene
15) Chrysene
16) Pyrene

VOCs:

1) Tetrachloroethylene
2) 1,2-dicholoroethane
3) Dichloromethane
4) trichloromethane (chloroform)
5) 1,1,1-dichloroethane
6) Tetrachloromethane (carbon tetrachloride)
7) Bromodichloromethane
8) Dibromochloromethane
9) Tribromomethane (bromoform)
10) Dichloroethene (trichloroethylene)

Organotin Compounds:

1) Monobutyltin
2) Dibutyltin
3) Tetrabutyltin
4) Monoctyltin
5) Dioctyltin
6) Tricyclohexyltin
7) Monophenyltin
8) Dimethyltin
9) MBT (monobutyltin cation)
10) DBT (dibutyltin cation)
11) TBT (tributyltin cation)
12) TTBT (tetrabutyltin cation)
13) MOT (Monooctyltin cation)
14) DOT (dioctyltin cation)
15) TPhT (triphenyltin cation)
16) TCyT (tricyclohexyltin cation)

CDFs:

1) 2,3,7,8-tetraCDF
2) 1,2,3,7,8-pentaCDF
3) 2,3,4,7,8-pentaCDF
4) 1,2,3,4,7,8-hexaCDF
5) 1,2,3,6,7,8-hexaCDF
6) 1,2,3,7,8,9-hexaCDF
7) 2,3,4,6,7,8-hexaCDF
8) 1,2,3,4,6,7,8-heptaCDF
9) 1,2,3,4,7,8,9-heptaCDF
10) OCDF

Others:

1) Chlorinated Paraffins C10-C13 (SCCP)
2) Hexabromocyclododecane (HBCD)
3) Benzene
4) Hexachlorobenzene
5) Ag (silver)
6) As (arsenic)
7) ethylbenzene
8) m/p- xylene
9) o- xylene
10) styrene
11) tetrachloroethene (perchloroethene)
12) tetrachloromethane (carbon tetraoxide)
13) toluene
14) tribromomethane (bromoform)
15) fenanthrene
16) 1,2,3-trichlorobenzene
17) 1,2,4-trichlorobenzene
18) 1,3,5-trichlorobenzene
19) 1,2,3,5-/ 1,2,4,5- tetrachlorobenzene
20) 1,2,3,4-tetrachlorobenzene
21) Pentachlorobenzene
22) flutsyrinate
23) Hexachlorobutadiene