Interreg
Baltic Sea Region

Co-funded by
the European Union

SUSTAINABLE WATERS
EMPEREST

Strategies and technological means for minimising organic micropollutant emissions from WWTPs

EMPEREST – ELIMINATING MICRO-POLLUTANTS FROM EFFLUENTS FOR REUSE STRATEGIES

University of Tartu and Gdańsk Water Utilities, 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.

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 (TUAS) (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

Version: September 2025

Authors: Taavo Tenno, Siiri Velling (University of Tartu), Marek Swinarski (Gdańsk Water Utilities)

Contributors: Christina Mürk, Risto Riiet, Aimar Kivirüüt (University of Tartu), Piia Leskinen (Turku University of Applied Sciences), Matthias Barjenbruch, Nikolaos Tzoupanos (Berlin University of Technology), Piotr Miakoto, Natalia Piętka (Water and Sewage Company Ltd of Szczecin), Povilas Reškevičius (Kaunas Water Ltd.), Ornella Mundi (Tartu Waterworks Ltd), Marlen Taggu (Tallinn Water Ltd), Mia Aitoukazzamane (Turku Region Wastewater Treatment Plant Ltd)

Layout: Laura Sarlin, City of Turku

Cover picture: © Taavo Tenno

How to cite: Tenno, T., Velling, S. & Swinarski, M. (2025, September). Strategies and technological means for minimising organic micropollutant emissions from WWTPs. Output 2.3 of the EMPEREST project, co-funded by Interreg Baltic Sea Region. University of Tartu and Gdańsk Water Utilities.

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.

Table of Contents

Annexes

List of Abbreviations

AOPs	advanced oxidation processes	PFHpA	perfluoroheptanoic acid
COD	chemical oxygen demand	PFHpS	perfluoroheptane sulfonic acid
DCMF	drum cloth media filter	PFHxA	perfluorohexanoic acid
DOC	dissolved organic carbon	PFHxS	perfluorohexane sulfonic acid
EU	European Union	PFNA	perfluorononanoic acid
EC	European Commission	PFNS	perfluorononane sulfonic acid
EPR	extended producer responsibility	PFOA	perfluorooctanoic acid
GAC	granular activated carbon	PFOS	perfluorooctane sulfonic acid
GC-MS	gas chromatography-mass spectrometry	PFPeA	perfluoropentanoic acid
HELCOM	Helsinki Commission	PFPeS	perfluoropentane sulfonic acid
IX	ion exchange	PFTrDA	perfluorotridecanoic acid
IXR	ion exchange resin	PFTrDS	perfluorotridecane sulfonic acid
LC-MS	liquid chromatography-mass spectrometry	PFUnDA	perfluoroundecanoic acid
LC-MS/MS	liquid chromatography-tandem mass spectrometry	PFUnDS	perfluoroundecane sulfonic acid
NF	nanofiltration	PFTrDS	perfluoroundecanoic acid
OMPs	organic micropollutants	PFUnDA	perfluoroundecane sulfonic acid
PAC	powdered activated carbon	PFUnDS	perfluoroundecanesulfonic acid
PAHs	polycyclic aromatic hydrocarbons	RO	reverse osmosis
PCBs	polychlorinated biphenyls	sPAC	superfine powdered activated carbon
PCMF	pile cloth media filter	SS	suspended solids
PE	population equivalent	TOC	total organic carbon
PFAS20 PFAS24	list of 20/24 PFASs	UWWTD	urban wastewater treatment directive
PFBA	perfluorobutanoic acid	VOC	volatile organic compounds
PFBS	perfluorobutane sulfonic acid	WWTP	wastewater treatment plant
PFDA	perfluorodecanoic acid	4-MTB	4-methyl-benzotriazole
PFDoDA	perfluorododecanoic acid	6-MTB	6-methyl-benzotriazole
PFDoDS	perfluorododecane sulfonic acid	Sum of PFAS	sum of per- and polyfluoroalkyl substances
PFDS	perfluorodecane sulfonic acid	PFAS Total	totality of per- and polyfluoroalkyl substances

1. Introduction

Organic micropollutants (OMPs) are trace-level contaminants increasingly recognized as a significant threat to environmental and human health. These substances commonly originate from a wide range of sources, including pharmaceuticals, personal care products, pesticides, hormones, microplastics, and various industrial compounds. Although typically present in concentrations ranging from nanograms to micrograms per litre, OMPs are biologically active, persistent, and capable of bioaccumulation — making them harmful even at minimal levels.

Wastewater treatment plants (WWTPs) are among the primary point sources of OMPs. While conventional treatment technologies are effective in removing nutrients and organic matter, they are largely ineffective in eliminating micropollutants. The chemical diversity and resistance of OMPs to standard treatment processes result in their continued release into aquatic environments, underscoring the urgent need for advanced treatment technologies and strengthened regulatory frameworks.

To address these challenges, the European Union adopted a revised Urban Wastewater Treatment Directive (UWWTD) in November 2024. The updated directive enhances environmental and public health protection by mandating stricter nutrient removal and introducing requirements for the elimination of micropollutants. Specifically, WWTPs serving populations of 150 000 population equivalents (PE) or more, as well as those over 10 000 PE discharging into high-risk areas, must implement quaternary treatment processes to effectively target and remove OMPs.

This report presents the results of two mobile pilot plant studies conducted in six Baltic Sea region cities as part of the EMPEREST project. The pilots aimed to evaluate the efficiency of advanced treatment technologies in reducing micropollutant concentrations in wastewater. The findings contribute to ongoing efforts to identify scalable, cost-effective, and environmentally sustainable solutions for mitigating the impact of OMPs in treated effluents.

Beyond the technical piloting, the EMPEREST project also provides strategic support to local authorities, wastewater treatment operators, and policymakers to strengthen the safety and sustainability of the water management cycle. The project specifically targets the elimination of PFAS (per- and polyfluoroalkyl substances) and other persistent organic micropollutants from wastewater. PFAS pollution has been identified as one of the most pressing environmental challenges in the Baltic Sea region, as highlighted in HELCOM’s latest holistic assessment (HOLAS 3). Local stakeholders often lack the necessary knowledge and technological capacity to address PFAS contamination effectively, while regional efforts are hindered by the absence of harmonized monitoring approaches. EMPEREST addresses these gaps by developing uniform methodologies, building capacity, and facilitating informed decision-making to support future investments.

List of partners

- Union of the Baltic Cities Sustainable Cities Commission c/o City of Turku (lead partner)
- Baltic Marine Environment Protection Commission - Helsinki Commission (HELCOM)
- University of Tartu
- Berlin University of Technology
- Turku University of Applied Sciences (TUAS)
- Gdańsk Water Utilities (piloting partner, Annex I)

- Water and Sewage Company Ltd. of Szczecin (piloting partner, Annex II)
- Tartu Waterworks Ltd (piloting partner, Annex IV)
- Tallinn Water Ltd (piloting partner, Annex V)
- "Kaunas water" Ltd. (piloting partner, Annex III)
- Turku Region Wastewater Treatment Plant (piloting partner, Annex VI)
- DWA German Association for Water, Wastewater and Waste DWA Regional group North-East
- Environmental Centre for Administration and Technology
- City of Riga

2. Context

Micropollutants are a diverse group of trace-level contaminants that include pharmaceuticals, endocrine-disrupting compounds, personal care products, industrial chemicals (such as PFAS), microplastics, and pesticides. Despite their low concentrations in the environment, many of these substances are persistent, bioaccumulative, and can pose serious risks to ecosystems and human health.

Conventional wastewater treatment systems, including primary, secondary, and tertiary stages are often ineffective at removing micropollutants. Although quaternary treatment is not yet widely implemented, a range of advanced technologies have demonstrated potential for significantly improving micropollutant removal. [1]

In addition to scientific information on the environmental impact of PFAS and the resulting regulations already established, the EMPEREST project output also clearly highlighted the PFAS contamination issue, as reflected in HELCOM's publication of methodological recommendations for the monitoring and assessment of PFAS in the aquatic environment [2]. During the study, a total of 2,385 biota samples were analyzed across the Baltic Sea region, with approximately half originating from marine environments. The dataset included fish (e.g. herring, perch, flounder), bird eggs, and mammal tissue (e.g. otter, reindeer, harbour porpoise).

Using the newly proposed EU Environmental Quality Standard (EQS) of 0.077 µg/kg wet weight for the sum of 24 PFAS (expressed in PFOA equivalents), the results revealed a high prevalence of PFAS contamination:

- 90% of all biota samples exceeded the threshold;
- 84% of fish muscle samples exceeded the threshold, posing direct risks to human consumption.

PFOS was the most frequently detected compound, contributing over 60% of exceedances, followed by long-chain PFAS such as PFNA, PFDA, and PFUnDA. Marine biota showed the highest PFAS concentrations, followed by lake fish, with riverine biota showing the lowest levels. Bird eggs consistently exceeded the threshold, even after applying a trophic conversion factor of 10, suggesting significant bioaccumulation. These findings highlight the urgent need for harmonized monitoring, improved analytical sensitivity, and policy action to address PFAS pollution in aquatic food webs.

In response to growing concerns over micropollutants, the European Union adopted a revised UWWTD in November 2024, which introduces new requirements aimed at improving the removal of micropollutants from municipal wastewater. The directive mandates the implementation of quaternary treatment processes in wastewater treatment plants serving populations of 150 000 PE or more, and in plants over 10 000 PE located in high-risk areas, such as drinking water catchments. These advanced treatment requirements specifically target the removal of pharmaceuticals, PFAS, and other persistent organic micropollutants. The directive also introduces a set of indicator substances to monitor treatment performance, marking a shift toward more consistent and stringent wastewater management across the EU.

To meet the new regulatory requirements and address the environmental risks posed by OMPs, a range of advanced treatment technologies have been developed and tested. These technologies are broadly categorized into two main groups: sequestration technologies, which remove contaminants by capturing them in another medium, and transformation technologies, which degrade or alter the pollutants through chemical or physical processes.

Sequestration methods include activated carbon adsorption (both powdered and granular forms), anion exchange resins, and membrane filtration techniques such as nanofiltration and reverse osmosis. These approaches are particularly effective for persistent compounds like PFAS and pharmaceuticals, though they may require additional handling of concentrated waste streams.

Transformation technologies, such as ozonation and other advanced oxidation processes (AOPs), chemically break down OMPs into less harmful substances. Ozonation is already widely implemented in several European countries and has proven effective in removing a broad spectrum of pharmaceuticals and endocrine disruptors. Emerging methods, including electrochemical oxidation, plasma treatment, and constructed wetlands offer additional potential but are currently limited to pilot or research-scale applications.

Among these options, ozonation and activated carbon adsorption are the most mature and widely adopted technologies in full-scale municipal wastewater treatment. Their combined use has shown enhanced removal efficiency and operational robustness, making them key candidates for meeting the performance benchmarks set by the revised UWWTD. Other technologies, such as ion exchange resins and membrane filtration (e.g., nanofiltration), are more resource-intensive and less commonly used in municipal settings but are increasingly considered for effective PFAS removal. Emerging methods, including electrochemical oxidation, foam fractionation, and constructed wetlands show promise but remain at the pilot or research stage. Their future applicability depends on further validation, cost-effectiveness, and scalability.

While several advanced technologies offer strong potential for removing OMPs, their effectiveness depends on careful optimization and integration into existing wastewater treatment systems. Key factors influencing successful implementation include operational complexity, energy demand, and cost-efficiency. These considerations are especially critical when planning large-scale upgrades, as required by recent regulatory changes. Selecting appropriate technologies must therefore balance removal performance with long-term sustainability and feasibility.

In summary, the growing presence of organic micropollutants in wastewater and aquatic environments has prompted both technological innovation and regulatory reform across the EU. The EMPEREST project contributes to this effort by advancing the understanding, monitoring, and removal of persistent contaminants such as PFAS, while supporting the implementation of effective treatment solutions at municipal scale.

2.1. UWWTD requirements for quaternary treatment and OMP removal

The revised UWWTD (2024/3019) introduces significant measures to address micropollutants, including PFAS. It mandates quaternary treatment for large WWTPs to remove a broad spectrum of micropollutants, particularly pharmaceuticals and PFAS.

To enhance the removal of micropollutants, revised UWWTD mandates the implementation of quaternary treatment technologies in WWTPs, based on plant size and environmental risk. By 2045, WWTPs serving ≥150 000 PE must install advanced treatment systems capable of effectively removing a broad spectrum of micropollutants. Additionally, WWTPs serving between 10 000 and 150 000 PE in high-risk areas—such as drinking water catchments—are required to adopt these technologies unless a detailed risk assessment demonstrates no significant threat to public or environmental health. This requirement is conditional: Member States must conduct risk-based evaluations to determine whether the presence and concentration of micropollutants justify the implementation of quaternary treatment. Technologies may include ozonation, activated carbon adsorption, membrane filtration, or other advanced processes proven to reduce micropollutant loads effectively.

To evaluate the performance of advanced wastewater treatment technologies, the revised UWWTD introduces the concept of indicator substances which are selected micropollutants that act as representative markers for broader contaminant groups. Their use enables consistent and standardized monitoring across WWTPs, helping assess the effectiveness of quaternary treatment processes such as ozonation and activated carbon. Monitoring the reduction of these substances also supports regulatory compliance by verifying that WWTPs meet the performance benchmarks set by the directive.

Revised UWWTD defines 12 indicator substances, divided into two categories. These substances are chosen based on their prevalence in wastewater, persistence and toxicity and their representativeness of broader micropollutant groups. Category 1, noted as easily measurable and commonly found consists of amisulpride, carbamazepine, citalopram, clarithromycin, diclofenac, hydrochlorothiazide, metoprolol and venlafaxine. Category 2 is about more variable or less frequently detected substances like benzotriazole, candesartan, irbesartan and mixture of 4-methylbenzotriazole and 6-methylbenzotriazole. WWTPs are required to achieve ≥80% average reduction in at least 6 of these indicator substances between influent and effluent.

Furthermore, revised UWWTD explicitly addresses PFASs, mandating their monitoring and removal in urban wastewater treatment. These requirements must align with the Environmental Quality Standards Directive (EQSD, 2008/105/EC), which sets environmental thresholds for pollutants in surface waters. A proposed revision to the EQSD introduces a limit of 4.4 ng/L for the sum of 24 PFAS compounds. While UWWTD does not specify exact limit values, it requires monitoring of PFAS concentrations and loads—particularly in areas where wastewater is discharged into drinking water catchments. Member States may choose to monitor either “PFAS Total,” “Sum of PFAS,” or both, and the European Commission is tasked with developing harmonized methodologies for these measurements by 2027.

To complement treatment efforts, the directive encourages the development of extended producer responsibility (EPR) schemes for products contributing to PFAS and microplastic pollution. This aligns with the polluter-pays principle, aiming to shift the financial and operational burden of pollution control from municipalities to manufacturers. Pharmaceutical and cosmetic producers must cover 80% of the costs for upgrading wastewater treatment plants to remove micropollutants, including infrastructure for the 4th treatment stage, monitoring and data collection and administrative costs of producer responsibility organizations. Producers must report annually on quantities of products placed on the market and their environmental risk.

2.2. Overview of available and future technologies for OMPs removal in wastewater treatment

In the context of the revised UWWTD, quaternary treatment technologies are essential for reducing OMPs such as pharmaceuticals and personal care products. Although the directive does not explicitly regulate PFAS compounds, their persistence and growing regulatory attention make it necessary to consider them alongside conventional micropollutants. Therefore, in the following sections, both typical organic contaminants and PFAS are addressed together. These quaternary technologies can be broadly divided into two main categories: Sequestration Technologies and Transformation (or Destruction) Technologies (Figure 1).

Sequestration Technologies

These methods remove contaminants from the water phase by concentrating them in another medium:

- **Sorption – Activated Carbon:** Both granular activated carbon (GAC) and powdered activated carbon (PAC) are well-established, cost-effective, and widely implemented options. They provide high removal efficiency for a broad range of pharmaceuticals and organic micropollutants.
- **Anion Exchange Resins:** Particularly relevant for strongly anionic and persistent pollutants such as PFAS. Anion exchange has already been demonstrated at full-scale plants for PFAS removal and is considered a viable option for future quaternary treatment steps.
- **Membrane Filtration:** Reverse osmosis (RO) and nanofiltration (NF) can achieve very high removal efficiencies, especially for PFAS and other persistent pollutants. NF/RO processes are already in use at full scale in water reuse and PFAS treatment applications. However, they generate a concentrate stream that requires further management.
- **Foam Fractionation**: A promising emerging technology that relies on surfactant properties of micropollutants and PFAS to separate them via foam formation. Initial research shows potential, especially for PFAS removal, but the method remains at a premature stage and is not yet applied at full scale.
- **Coagulation (Specialty Coagulants):** Specialty coagulants can improve the removal of certain charged micropollutants but are less commonly applied as a stand-alone quaternary treatment option.

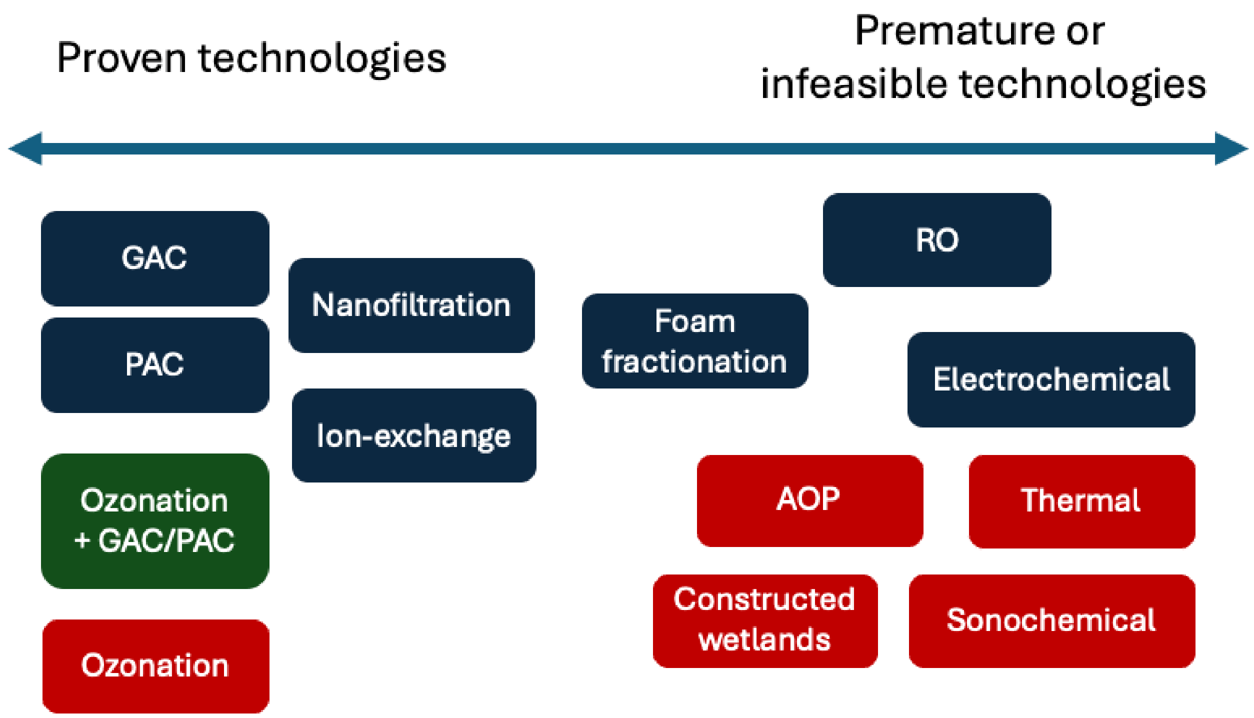

Figure 1. Selection of major technologies used for quaternary wastewater treatment (sequestration technologies – blue, transformation technologies - red, combined technologies – green). AOP - advanced oxidation processes, GAC - granular activated carbon, PAC – powdered activated carbon, RO – reverse osmosis.

Transformation or Destruction Technologies

These methods break down micropollutants through chemical or physical processes:

- **Redox Treatment**:
  - **Ozonation** is the most established transformation technology in wastewater treatment. It is already applied at full scale across Europe (e.g., Switzerland, Germany, Sweden) and has demonstrated high efficiency in removing a wide spectrum of pharmaceuticals and other organic micropollutants.
  - Other redox-based methods such as electrochemical oxidation and plasma treatment are still largely at the research or pilot stage.
- **Constructed Wetlands** (engineered reed beds): A nature-based solution that combines biological transformation with sorptive and accumulative mechanisms in soils and plant biomass. Constructed wetlands can provide additional polishing for nutrients and selected micropollutants, with relatively low energy demand. However, removal efficiency for pharmaceuticals and PFAS is inconsistent, and their application requires large land areas. They are best considered as complementary polishing steps rather than stand-alone quaternary treatment solutions.
- **Other Emerging Methods:** Sonochemical, thermal, and biological destruction technologies have been tested primarily at laboratory or pilot scale and are not yet viable full-scale alternatives for quaternary treatment.

Among these options, only **activated carbon (GAC/PAC)** and **ozonation** have proven reliable, cost-effective, and scalable in full-scale municipal wastewater treatment plants. These two technologies are often applied in **combination (ozone followed by GAC)**, which enhances overall pollutant removal, minimizes by-product formation, and provides operational robustness. This combined approach have been implemented and recognized as a practical pathway to meeting the EU directive's requirement of at least 80% removal of selected indicator substances.

Given the persistence of PFAS compounds, **anion exchange resins** and **nanofiltration** have been applied at full scale for PFAS removal. These have been often used in drinking water and industrial wastewater treatment. Their relevance for municipal quaternary treatment is increasing and should be seriously considered in light of PFAS regulation. These technologies are considered more resource- and cost-intensive than ozone or activated carbon alone but may be necessary if PFAS removal is a concern.

In summary, the most mature and widely applicable quaternary treatment options for municipal wastewater are ozonation and activated carbon (GAC/PAC), either separately or in combination. Anion exchange and nanofiltration represent additional viable technologies where PFAS are present. Other transformation and destruction methods remain at the experimental stage and are not yet reasonable alternatives for large-scale implementation.

Table 1: Overview of Quaternary Treatment Technologies for PFAS and micropollutant removal [3]

Technology	Category	Full-scale implementation	Typical performance	Advantages	Limitations / Challenges
Granular Activated Carbon (GAC)	Sequestration (Sorption)	Widely implemented in Switzerland, Germany, Sweden, etc.	High removal of many organic micropollutants.	Proven, robust, relatively simple operation; regeneration possible.	Performance declines as carbon saturates; replacement/regeneration needed.
Powdered Activated Carbon (PAC)	Sequestration (Sorption)	Applied in several full-scale WWTPs	High removal efficiency, requires dosing optimization; effective for organic micropollutants.	Flexible operation; dosing adjustable to load; can be retrofitted into existing basins.	Handling/disposal of PAC-laden sludge; potential impacts on sludge reuse.
Nanofiltration / Reverse Osmosis (NF/RO)	Sequestration (Membrane)	Full-scale in water reuse and PFAS treatment	More effective for removal of PFAS.	High efficiency, broad-spectrum removal.	Produces a concentrate stream that must be managed; high energy demand.
Anion Exchange Resins (IX)	Sequestration	Applied full-scale for PFAS removal in drinking water and industrial effluents.	Very high removal of PFAS.	Selective and effective for persistent anionic compounds.	Spent resins require regeneration or disposal; costs can be high.
Ozonation (O_3)	Transformation (Redox)	Full-scale application in Switzerland and other EU countries.	70–95% removal of pharmaceuticals and endocrine disruptors.	Highly effective for a wide range of micropollutants; fast reaction kinetics.	Risk of by-products (e.g., bromate, NDMA); requires careful process control, less effective for PFAS.
Ozone + GAC (combined)	Transformation + Sequestration	Demonstrated at full scale (e.g., Neugut WWTP, CH; Stengården WWTP, SE).	Consistently achieves >80% removal across broad spectrum of compounds.	Synergy: ozone reduces load, GAC polishes residuals and by-products; robust solution.	Higher complexity (two-stage system); requires monitoring and process integration.
Electrochemical, Plasma, Thermal, Sonochemical, Biological	Transformation	Only pilot- or lab-scale applications.	Case-specific removal, mostly in controlled trials.	Potential for targeted degradation.	Not mature; energy-intensive; uncertain by-products.

2.3. Potential opportunities for the reuse of treated water

Quaternary treatment is increasingly recognized as a critical enabler for safe and sustainable water reuse. By significantly reducing concentrations of OMPs, including pharmaceuticals and PFAS, advanced treatment technologies such as ozonation, activated carbon filtration, membrane processes, and UV disinfection improve effluent quality to levels suitable for reuse in agriculture, industry, and even indirect potable applications.

At the European level, Regulation (EU) 2020/741 sets minimum requirements for the reuse of treated urban wastewater, primarily for agricultural irrigation. It defines four water quality classes (A to D) based on intended use and irrigation method, and mandates risk management plans to ensure environmental and public health safety. This regulation complements the revised UWWTD, which promotes water reuse as part of a broader circular economy strategy, especially in water-stressed regions.

Scientific studies confirm that quaternary treatment, particularly combinations of coagulation, membrane filtration (UF/NF), and UV disinfection can reliably meet reuse standards while remaining cost-effective. Moreover, reuse of treated wastewater can contribute to nutrient recovery (e.g., nitrogen, phosphorus, potassium), reducing the need for synthetic fertilizers and supporting sustainable agriculture. [4]

While EMPEREST pilot studies focused primarily on micropollutant removal, the inclusion of modular treatment steps and optional UV disinfection demonstrates the potential to adapt these systems for future reuse scenarios, aligned with EU policy and environmental goals.

3. EMPEREST technology pilots

3.1. Investment roadmaps of the pilot plants

The project introduces two mobile pilot plants to test advanced treatment technologies and support future large-scale implementation. Objectives of the piloting activity is to demonstrate and evaluate advanced treatment technologies for micropollutant removal, including PFAS, and provide data for informed decision-making on technology adoption. The project is structured into multiple phases, including design, procurement, assembly, piloting at different sites, and transfer logistics. To manage these complex and interdependent activities, a roadmap approach has been adopted. [5], [6]

Pilot plants were designed as containerized, modular systems with flexible connections which main process units are:

- influent pumping (0.5–5 m^3/h; 3-15 m^3/h);
- pile cloth media filter (PCMF)/ drum cloth media filter (DCMF) – solids removal; optional PAC dosing;
- ozonation – advanced oxidation for OMPs' degradation (adjustable contact time);
- filtration – dual media filter (DMF), GAC, optional ion exchange;
- UV Disinfection – optional step for microbial inactivation and water reuse potential;
- monitoring node – online sensors for pH, turbidity, UV254, flow.

Monitoring and analysis were categorized as

- Level I: Online automation (flow, pH, turbidity, UV254);

- Level II: Lab tests for COD, TOC, DOC, SS, nutrients, bromide;
- Level III: PFAS (LC-MS/MS & AOF sum parameter) and other micropollutants (priority classes A–D).

During the initial phase of the project, as part of the roadmap development, it was planned that each piloting WWTP would analyse a comprehensive panel of priority substances, specifically covering classes A–C or A–D, at least twice during their piloting period. WWTP operators that conducted pilot tests procured analytical services for OMPs, focusing on the main priority classes identified in Table 2.

Priority substances are chemicals identified as posing significant risks to water environments and human health, such as pesticides, pharmaceuticals, and industrial chemicals. These substances are grouped into priority classes based on their environmental impact and regulatory status, including “priority substances” and the more hazardous “priority hazardous substances,” which are particularly toxic, persistent, and likely to bioaccumulate. The goal for priority hazardous substances is to phase out emissions entirely within a set timeframe.

The European Union’s Water Framework Directive (WFD) establishes a legal framework for protecting surface and groundwater. It requires Member States to monitor and progressively reduce emissions, discharges, and losses of priority substances. The list of priority substances (Annex X of the WFD) is regularly reviewed and updated, and environmental quality standards (EQS) are set for each substance to ensure good chemical status of water bodies [7].

Table 2: Prioritisation of OMP chemical analysis for piloting WWTPs. Priority classes are based on previous effluent analysis at the WWTPs, current regulations and upcoming legislative changes. [5]

Priority Class A[1]	**Priority Class B**[2]	**Priority Class C**[3]	**Priority Class D**[4]
Chloroalkanes, C10-13	Amisulprid	Diuron	Other WFD Annex X substances and potential new substances proposed to be added there
Tributyltin compounds	Carbamazepine	Isoproturon	
Polychlorinated biphenyls (PCBs)	Citalopram	Naphthalene	
Hexabromocyclododecanes (HBCDD)	Clarithromycin	Tetrachloroethylene	
Phthalates (including DEHP)	Diclofenac	Polychlorinated dibenzofurans (PCDFs)	
	Hydrochlorothiazide	Terbutryn	
	Metoprolol	Silver (Ag)[5]	
	Venlafaxine	Hexachlorobenzene	
	Benzotriazole	Benzene	

[1] Substances previously found in high concentrations in at least one piloting WWTP’s effluent. Each piloting WWTP will focus on the relevant ones to their own facility.
[2] Substances proposed as evaluation criteria for advanced effluent treatment technologies by the new UWWTD update proposal. As the recast directive has not been approved yet, the substances under this class might change accordingly.
[3] Substances that have been detected in piloting WWTPs effluents above LOQ values, giving potential reference points and showing degradation effects.
[4] Although silver is not an organic substance, it is of increasingly high concern in wastewater.

Priority Class A[1]	Priority Class B[2]	Priority Class C[3]	Priority Class D[4]
	Candesartan		
	Irbesartan		
	Mixture of 4-methylbenzotriazole and 6-methylbenzotriazole		

At the end of second your of project activities, in 2024, the revised UWWTD was released, and an updated indicator list of micropollutants became available [8]. Following this, some pilot sites placed greater emphasis on the relevant indicator list but continued to analyse a broader range of OMPs, such as PFAS, across the widest possible spectrum.

The two pilot plants were procured through two different public procurement procedures.

Pilot Plant 1. Procurement was divided into four separate tenders, covering:

- pile cloth media filter (PCMF);
- ozonation and UV systems;
- analyses package;
- GAC filters and assembly.

Weekly coordination meetings were held to ensure timely assembly and integration of all components.

Pilot Plant 2. A single comprehensive tender was completed in July 2023, and the contract was signed with the selected contractor. The procurement process included the following stages:

- Stage I: Conceptual design based on detailed guidelines developed by Gdańsk Water Utilities;
- Stage II: Construction and assembly;
- Stage III: Commissioning and operator training.

The previously prepared roadmaps provided a clear visualization of what happens when, ensuring that all partners understand the sequence of tasks, key dependencies, and critical milestones throughout the project lifecycle. The piloting timeline was as follows:

Tartu WWTP: until Aug 2023

Tallinn WWTP: Sept 2024 – Jan 2025

Turku WWTP (Finland): Feb – June 2025

Gdańsk WWTP: Apr – Aug2024

Szczecin WWTP: Sept 2024 – Jan 2025

Kaunas WWTP: Feb – June 2025

As shown in the timelines, the pilot plants were transferred between different wastewater treatment plants, following the strategy outlined below:

- Each site: 5-month cycle;
- Deinstallation (1 week) → Transport (1 week) → Reinstallation (1 week) → Startup (1–3 weeks) → Testing (up to 3 months).

As outlined in the roadmaps, the expected outcomes of the piloting activities are:

- Comparative performance data for advanced treatment technologies.
- Recommendations for cost-effective, scalable solutions for micropollutant and PFAS removal.

- Enhanced knowledge-sharing among Baltic Sea region stakeholders.

Using roadmaps provides significant coordination advantages for complex, multi-partner projects. They enable alignment across multiple partners and countries by presenting a unified timeline that clearly shows the sequence of activities and interdependencies. This improves communication of responsibilities and deadlines, reducing the risk of misunderstandings. Roadmaps also support early identification of bottlenecks and risks, allowing for proactive adjustments before delays occur. Additionally, they facilitate efficient resource planning, as stakeholders can anticipate upcoming tasks and allocate staff, equipment, and budget accordingly. Overall, this structured approach ensures transparency, enhances collaboration, and contributes to the timely and successful implementation of project activities.

3.2. Mobile pilot plant technology

Based on the evaluation of quaternary treatment technologies outlined in the previous chapters, the pilot plants were designed to apply technologies that have already demonstrated effectiveness at full scale. Two independent, mobile, fully automated pilot units were constructed, each housed within a standard shipping container. One pilot plant was built in Gdansk, Poland (Pilot A), and the second one in Tartu, Estonia (Pilot B).

The core treatment technologies tested in both pilots were the same: pre-filtration (PCMF/DCMF), ozonation, GAC, and UV disinfection. The technical equipment was installed in a modular manner, allowing each treatment step to be operated either individually or in sequence (Figure 2). The hydraulic capacity of upstream units was intentionally designed to exceed that of the downstream units, ensuring operational flexibility and stable flow distribution during combined operation.

In addition to the core processes there were some additional differences between the two pilot plants:

- Pilot plant A (Gdańsk) was equipped with an ion exchange (IX) unit –the selected ion exchange resin was specifically chosen for PFAS removal;
- Pilot plant B (Tartu) incorporated nanofiltration (NF) to assess the potential of membrane-based barriers for PFAS removal in municipal wastewater context, with the aim to analyse the technology in the context of other OMPs;
- Pilot Plant B (Tartu) unit was designed to be reconfigurable for testing superfine powdered activated carbon (sPAC) dosing.

Conceptual process flow diagrams and photos of both configurations are presented in the figures below (Figure 2-4).

Both pilot plants were fully automated and equipped with online water quality monitoring instruments, including flow meters, UV254 absorbance sensors, pH, and turbidity probes.

A detailed description of the technical equipment and operational characteristics is provided in the annexes to this report (Annexes I–VI: Pilot Plant Test Reports).

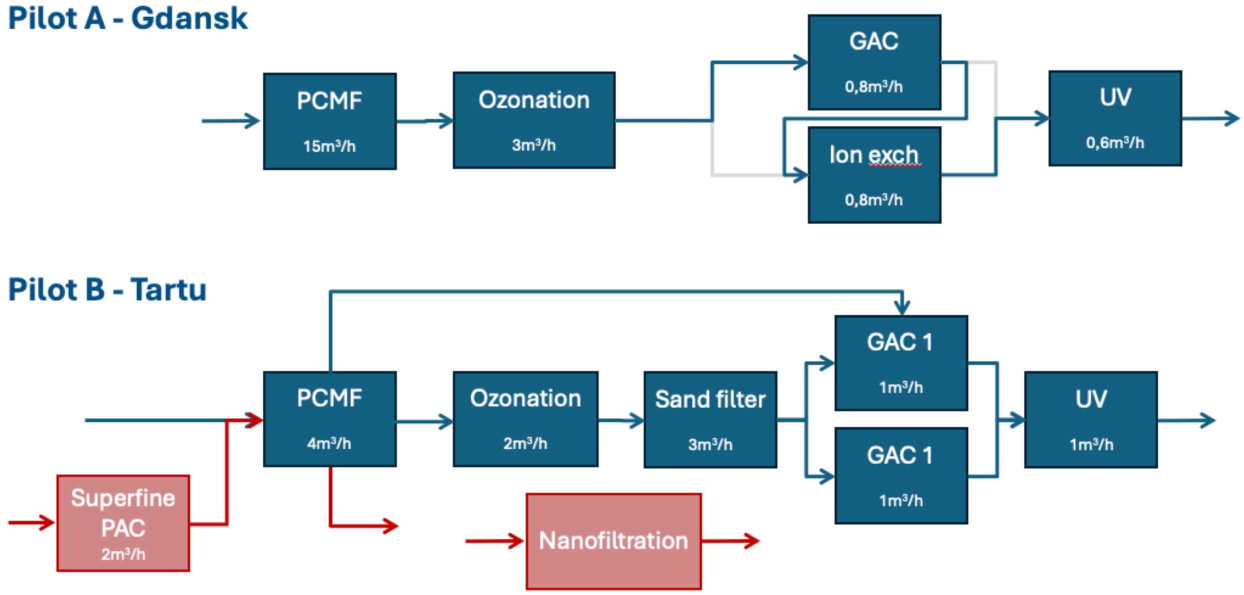

Figure 2. Conceptual process block diagrams of two pilot plants used in the study.

Figure 3. Pilot plant A internal installations.

Figure 4. Pilot plant B internal installations.

3.3. Micropollutants and analytical methods

The EMPEREST project pilots implemented a diverse range of chemical monitoring strategies to assess the occurrence and removal of micropollutants in municipal wastewater treatment plants across the Baltic Sea region. The analytical scope and approach varied between sites, reflecting differences in start-up periods, the prior experience of each WWTP, and the updated requirements of the UWWTD adopted at the end of 2024.

To ensure a comprehensive evaluation of treatment effectiveness and micropollutant removal, each pilot site commissioned chemical analyses with slightly different strategies. These differences were shaped by the operational readiness of the pilot plants, the historical monitoring practices at each location, and the evolving regulatory landscape. As a result, the number of sampling series, the range of pharmaceuticals and PFAS compounds analysed, and the inclusion of other organic OMPs varied from site to site.

The following Table 3 summarises the analytical scope and key findings for each EMPEREST pilot, highlighting the number of sampling series, the breadth of pharmaceutical and PFAS monitoring, the concentration ranges observed, and the extent of additional OMP screening.Across all EMPEREST pilot sites, the chemical analyses focused on:

- Pharmaceuticals (later during project as per UWWTD indicator list);
- PFAS (per- and polyfluoroalkyl substances, typically 13–30 compounds);
- Other OMPs: including pesticides, herbicides, estrogens, phenols, benzotriazoles, PCBs, PAHs, VOCs, organotin compounds, and dioxins/furans (mainly in Tartu and, to a limited extent, in Gdańsk/Szczecin/Kaunas).

Sampling and analysis were performed using accredited laboratory methods, primarily LC-MS/MS for pharmaceuticals and PFAS, and GC-MS for some pesticides and phenols. Samples were collected at key points: pilot influent and after each treatment stage (e.g., ozonation, GAC, sand filtration, IX treatment and nanofiltration).

Table 3: Sampling frequency, analytical coverage, and detected micropollutants

	No of sampling series	No of pharmaceuticals analysed/detected	No of PFAS analysed/detected	No of other MPs analysed/detected
Annex 1 Gdansk Water Utilities	15 for PFAS, 6 for OMPs	11/10	20/6	herbicides: 3/2 estrogens:2/0 phenols: 2/0 benzotriazoles: 2/2
Annex 2 Water and Sewage Company Ltd. of Szczecin	9	12/11	23/11	Not specified
Annex 3 Kaunas Water Ltd	10	11/10	49/8	Phthalates: 10/5
Annex 4 Tartu Waterworks Ltd	Twice per month	149/63	24/8	Pesticides: 301 compounds Phthalates: 12 PCBs: 32 PAHs: 16 VOCs: 10 Organotin compounds: 16 CDFs (dioxins/furans): 10 Others: 23
Annex 5 Tallinn Water Ltd	4	12/11	13/10	None
Annex 6 Turku Region Wastewater Treatment Plant Ltd	30	10/9	30/12	Herbicides 2/0

Sampling campaigns varied in intensity, from 4–10 discrete series (Tallinn, Szczecin, Kaunas) to twice-monthly or weekly campaigns (Gdańsk, Tartu, Turku). The number of pharmaceuticals analysed ranged from 10–12 at most sites (with detection rates typically high), up to 149 at Tartu, where 63 were detected. Pharmaceutical concentrations in the pilot plant influent ranged from 100 to 17 000 ng/L. As a result of the treatment processes, at least 60% removal efficiency was achieved, although removal rates typically ranged from 80% to 100%.

PFAS monitoring was also extensive, with 13–49 compounds analysed per site. Detection rates varied, with 6–12 PFAS typically found. Concentration ranges for individual PFAS were generally 1–20 ng/L, but some sites (Tallinn, Turku) also reported TFA (trifluoroacetic acid) at much higher levels (up to 720 ng/L). Tartu wastewater treatment plant piloting team explicitly measured the sum of PFAS in treated effluent and compared the results to the proposed EU Environmental Quality Standard (EQS) of 4.4 ng/L (expressed as PFOA equivalents). This approach enabled a direct assessment of compliance with forthcoming regulatory requirements and provided a clear benchmark for evaluating the effectiveness of advanced treatment technologies in reducing total PFAS concentrations.

Broader screening for other micropollutants was limited to a few sites. Tartu conducted the most comprehensive analysis, screening for over 400 additional OMPs (including pesticides, phthalates, PCBs, PAHs, VOCs, organotins, dioxins/furans, and others), though most were not detected. Gdańsk, Szczecin, and Kaunas WWTP piloting teams included a small set of herbicides, estrogens, phenols, and benzotriazoles. Turku WWTP tested for herbicides but found none.

Key findings include:

- Tartu WWTP tests stood out for the breadth of its chemical analysis, both in pharmaceuticals and other OMPs.
- Szczecin WWTP reported the highest pharmaceutical concentrations, suggesting a higher pollution load or different influent characteristics.
- Tallinn and Turku piloting teams included TFA in their PFAS analysis, revealing persistent short-chain PFAS not efficiently removed by current technologies.
- Detection of other OMPs was generally low, with most compounds below quantification limits except for pharmaceuticals and PFAS.

3.4. Economic feasibility of quaternary treatment

Consistent with scientific articles, the project results support that among the quaternary treatments currently available for the removal of micropollutants, the most effective and extensively studied are adsorption onto activated carbon—either in powdered (PAC) or granular (GAC) form—and AOPs, with ozonation being the most widely adopted method [9].

The cost analysis presented is based on preliminary estimate**s** derived from research, pilot studies and experience in the field. These figures offer initial insights into the potential cost implications of implementing advanced treatment technologies such as GAC and ozonation.

It is important to note that our pilot studies have not yet been conducted at a scale sufficient to accurately reflect the full operational costs of a large-scale wastewater treatment plant. The cost of implementing new treatment process is highly dependent on the technology type, design configuration, and site-specific conditions, making direct comparisons between different WWTPs challenging and potentially unreliable.

Regarding the economic analysis, both capital expenditure (CAPEX) and operational expenditure (OPEX) are considered in this analysis. About OPEX, the annual per-capita costs for each quaternary treatment process vary significantly depending on key operating parameters: the ozone concentration maintained in the contact tank, the interval between two regenerations of GAC, and the dosage of PAC as well as the percentage of extracted sludge sent to incineration relative to the total sludge generated. It should also be noted that the operating parameters of all quaternary treatment technologies must be carefully optimized based on the specific water quality characteristics, particularly the organic matter content, which competes with micropollutants for adsorption and significantly influences treatment efficiency.

Ozonation effectively degrades a wide range of micropollutants and improves their biodegradability, but may generate various unknown by-products, some of which could still pose toxicological risks. [10] This might require additional treatment steps to mitigate the risk, such as sand filtration or biological post-treatment which increase overall costs. Activated carbon adsorption is a robust and flexible method that does not produce harmful by-products but removes a broad spectrum of micropollutants. GAC systems require periodic, possible energy-intensive regeneration and may generate waste streams requiring incineration. Although PAC systems could require a lower initial capital investment than GAC systems and provide comparable adsorption efficiency, they demand continuous dosing and cannot be regenerated. This leads to higher long-term operational costs, primarily due to increased sludge generation.

During the project, we also tested the resin Amberlite PSR2+. This material is a gel-type, strong-base anion exchange resin functionalized with tri-N-butylamine which is widely used in resins designed for PFAS removal from water. Its presence imparts a higher degree of hydrophobicity to the ion exchange sites compared to conventional strong-base anion exchange resins, enhancing its affinity for hydrophobic contaminants. Sources from ion exchange resin manufacturers claim that CAPEX and OPEX costs compared to GAC can be similar or even lower. When implementing either technology, it is important to consider operating time as well as disposal or reuse costs. At the same time, IX resins are highly effective at removing long-chain PFAS compounds. [11]

Annual per-capita costs of quaternary treatment processes are more strongly influenced by the selected operational parameters than by the overall capacity of the wastewater treatment plant. For treatment plants serving fewer than 100,000 PE, the cost per dosing event tends to be higher and is more sensitive to the concentration of micropollutants and the specific operational practices employed at each facility. The first approximation cost estimates presented in this report include both capital expenditures (CAPEX) and operational expenditures (OPEX), providing a comprehensive view of financial implications from initial investment through ongoing operation and maintenance.

Depending on the regeneration interval of GAC, which typically ranges from 6 to 36 months, the annual operating cost can vary between €3–12 per PE. For ozonation, the cost is influenced by the applied ozone concentration (2–10 mg/L), resulting in an estimated €2–6/PE/year. [1] The cost of powdered activated carbon (PAC) treatment varies widely, depending primarily on the population equivalent (PE) and the development stage of the treatment process.

Depending on the treatment plant specific conditions (f.e dissolved organic carbon content), technology configuration and energy and material tradeoffs, the annual operating costs of quaternary treatment of wastewater could be in the range of 0,1-0,5€/m^3 [12]. Rizzo et al have reported a CAPEX in the range of 0.035–0.05 Euro/m^3 of treated wastewater (30 years depreciation for civil works and 15 years for mechanical equipment, 10 for electrical equipment), and an OPEX of 0.04 Euro/m^3 of treated wastewater (including electric energy, maintenance, additional analyses and workload, oxygen input), practically independent of the process adopted. Pistocchi et al have gathered indicative ranges of costs and cost functions proposed in the literature about various European wastewater treatment plants and proposed an expenditure function that is referred as a practical working assumption for a preliminary assessment of aggregated costs, at the European scale, taking into account the capacity of the plant [3].

In conclusion, while both ozonation and activated carbon adsorption are effective quaternary treatment options, their cost-efficiency depends heavily on site-specific operational parameters, and further large-scale validation is needed to refine full-scale cost estimates. IX can be applied for micropollutant removal, especially as polishing step in combination with advanced oxidation or adsorption.

4. Pilot studies

4.1. Baseline micropollutant conditions

Pilot trials of quaternary wastewater treatment were conducted using two independent containerized pilot plants, which were operated at a total of six municipal wastewater treatment plants. The pilots aimed to evaluate the efficiency of advanced treatment technologies in reducing micropollutant concentrations in wastewater.

The sets of micropollutants analysed, varied between treatment plants. Since the revised UWWTD entered into force during the project period, facilities that carried out pilot trials in the early stages of the project were in a more challenging position, as standardized monitoring frameworks were not yet fully established. Analytical laboratories were simultaneously developing and validating new methods, which meant that in later stages of the project, the participating plants were able to focus more precisely on the UWWTD indicator substances and could carry out a greater number of analyses, as testing costs had decreased.

At a later stage of the project, the piloting WWTPs were able to set new objectives based on the indicator substances specified in the revised UWWTD. Their main goal was to assess compliance with these updated requirements, while also addressing the broader challenge of micropollutant removal.

Because the pilot trials were performed at different times and according to slightly different testing protocols, the results cannot be directly compared or aggregated across all sites. Instead, the following section highlights the key findings and main messages derived from the trials, with selected examples of raw data from individual treatment plants used to illustrate the outcomes.

It should also be noted that the concentrations of micropollutants in the effluents of the participating treatment plants varied substantially. The following figures (Figure 6-7) present selected results for both OMPs and PFAS across different WWTPs. As shown, the baseline levels of OMPs differ widely between plants, underlining the need for an individualized approach when assessing and planning quaternary treatment solutions.

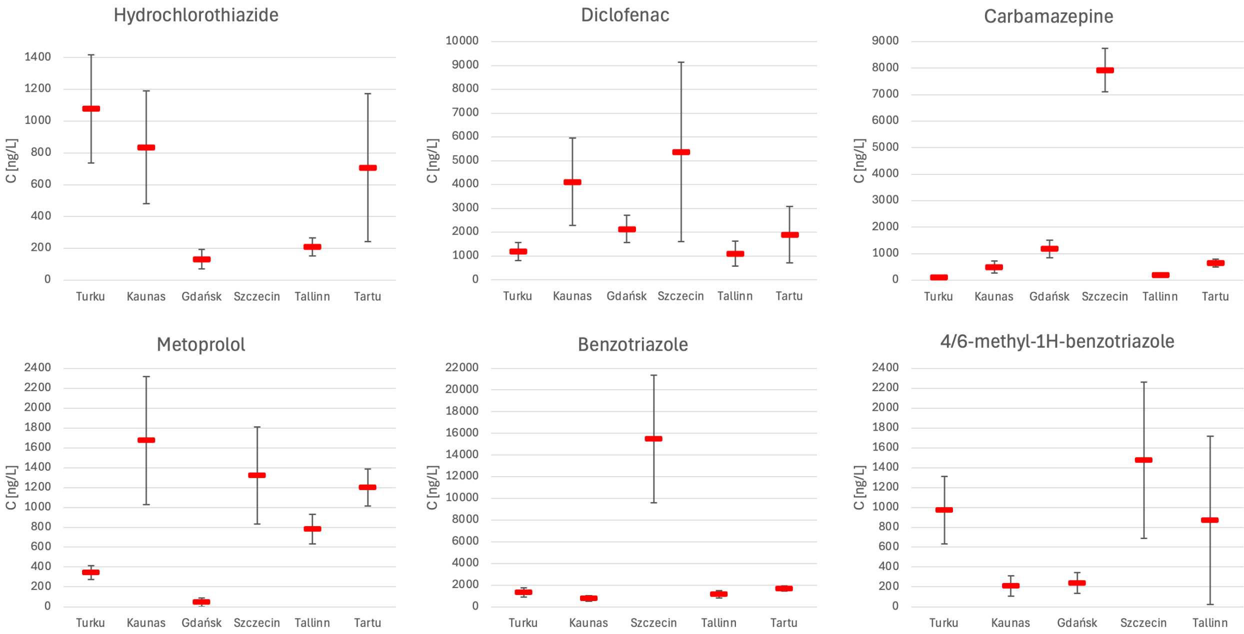

Figure 5: Average effluent concentrations of selected micropollutants at the WWTPs during the pilot plant operation period

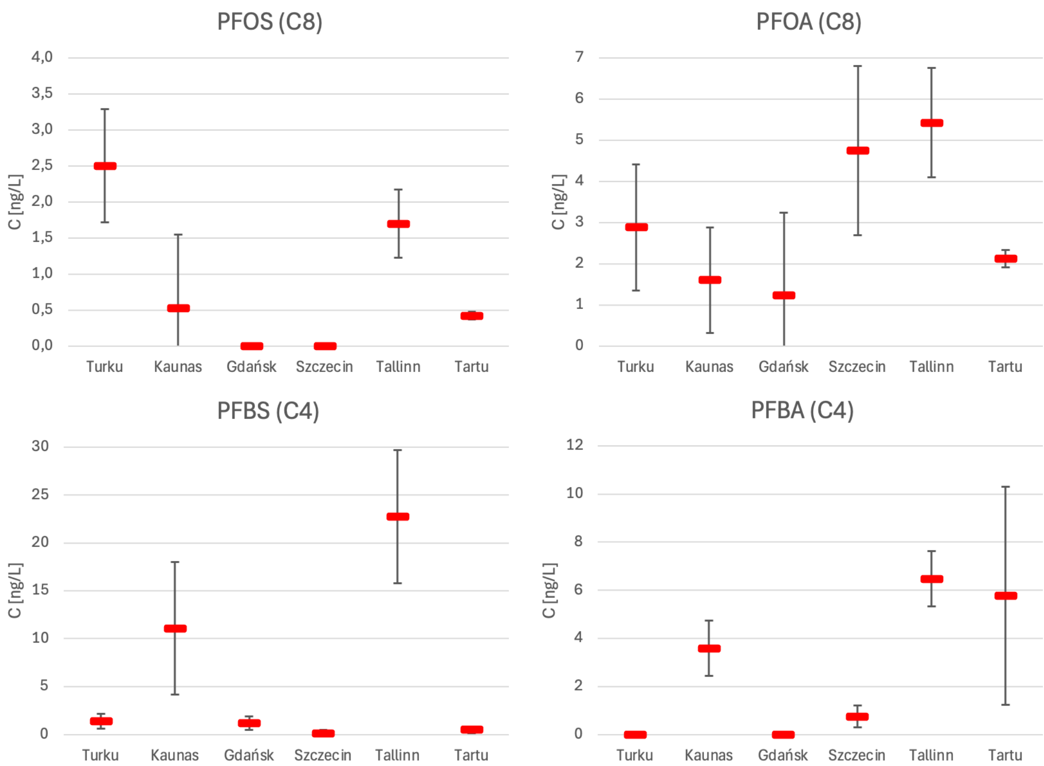

Figure 6: Average effluent concentrations of selected PFAS compounds at the WWTPs during the pilot plant operation period

4.2. Ozonation and GAC for organic micropollutant removal

As ozonation and GAC treatment formed the core technological solutions in all pilot trials, each participating wastewater treatment plant was able to gain practical experience with these processes. However, the scope of testing and the number of parameters analysed varied considerably across the piloting procedures. All pilot plants tested ozonation and GAC both as stand-alone processes and in combination. At the same time, there were notable differences in ozone dosages and in the contact times applied in the respective processes. Please see the detail test reports in the annexes.

In most test series, the focus was limited to the performance of the quaternary treatment technologies themselves. In some cases, however, the entire activated sludge process was also assessed. For example, results from the Szczecin WWTP show that the activated sludge step already reduces the concentrations of several pharmaceuticals, such as clarithromycin and metoprolol, to a large extent. In contrast, more persistent compounds, including diclofenac, amisulpride, and carbamazepine, remain essentially unaffected (see Annex I).

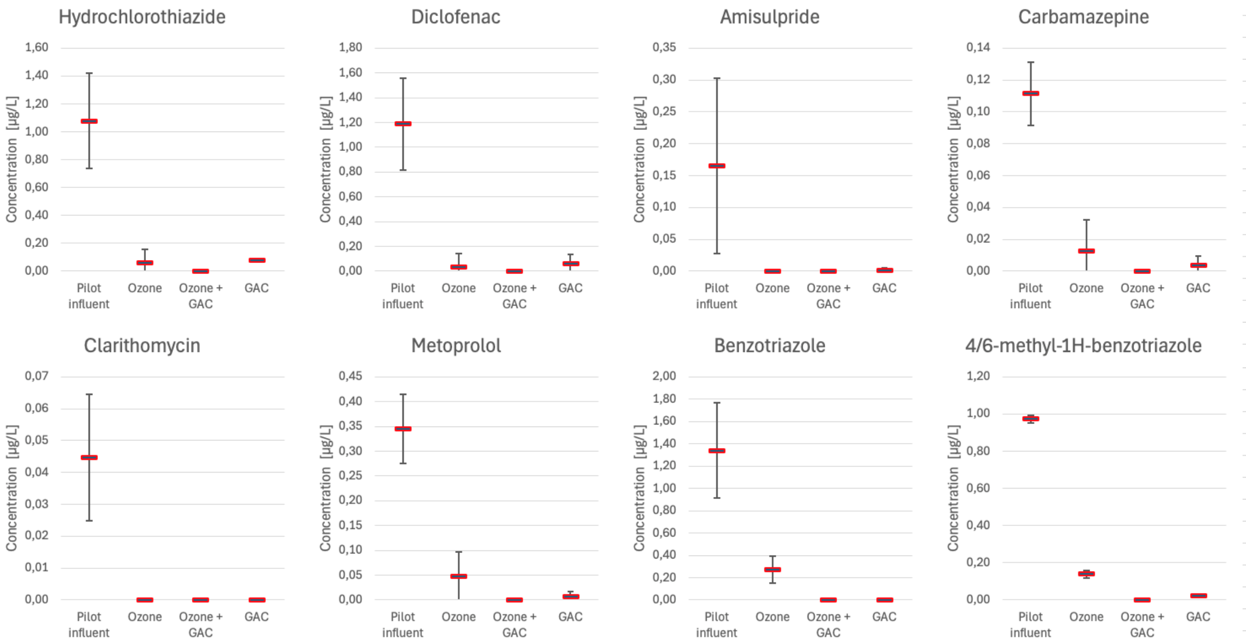

Figure 7. Concentrations of OMPs during the pilot plant operation in Turku (Annex VI).

Overall, the majority of test series demonstrated that both ozonation and GAC treatment performed very well in removing persistent OMPs. Removal efficiency was strongly dependent on ozone dosage and contact time. Results from the Turku WWTP illustrate that ozonation and GAC can have different effects depending on the substance. Some compounds, such as amisulpride and diclofenac, were reduced equally well by both technologies, whereas others, such as hydrochlorothiazide, metoprolol and benzotriazoles, showed higher removal in the GAC filter (Figure 5).

As outlined in Annex VI, during the initial testing period, the pilot plant experienced a two-week episode of unusually high suspended solids in the inflow, which significantly reduced the efficiency of the GAC filter. High SS concentrations reached both the ozonation unit and GAC B, while GAC A received treated wastewater with lower SS levels due to an additional sand filter located downstream of the ozonation unit. This filter effectively removed suspended solids before the water reached GAC A, which explains the earlier efficiency drop observed in GAC B. The event also suggests that pre-ozonation has limited impact on SS removal. Overall, this highlights the sensitivity of the quaternary treatment stage to variations in inflow quality. Given the technical complexity and cost of quaternary treatment, maintaining its efficiency requires continuous monitoring and control of key water quality parameters. Defining acceptable inflow limits and ensuring consistent operational oversight are essential to prevent similar performance issues.

In conclusion, the pilot testing demonstrated that while the efficiency of the GAC filter declined over three months of continuous operation, the combined application of ozonation and GAC consistently ensured nearly complete removal of persistent organic micropollutants (OMPs). This confirms that both technologies are effective for OMP removal, particularly when used in sequence.

4.3. Ozonation and GAC for PFAS removal

In all pilot trials, PFAS were analysed using targeted GC/MS methods. In most cases, a list of 24 PFAS substances (PFAS24) was applied. Concentrations of PFAS in the influent of the wastewater treatment plants were generally relatively low, typically below 100 ng/L. At two of the sites, however, trifluoroacetic acid (TFA) concentrations were also measured and found to be significantly higher, in the range of 600–800 ng/L.

Overall, the results indicate that the effect of ozonation on PFAS removal was limited. The impact depended strongly on the chain length of the PFAS molecules. For long-chain compounds, ozonation led to a measurable reduction in concentrations, whereas for short-chain PFAS the concentrations either remained unchanged or even increased.

For example, results from the Turku pilot plant show that C8 compounds such as perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) decreased in concentration following ozonation, while C4 compounds such as perfluorobutanoic acid (PFBA) and perfluorobutane sulfonate (PFBS) increased. Similarly, small increases were also observed for very short-chain PFAS such as trifluoroacetic acid (TFA) (with an increase of approximately 50 ng/L in the Turku trials) and trifluoromethanesulfonic acid (TFMS).

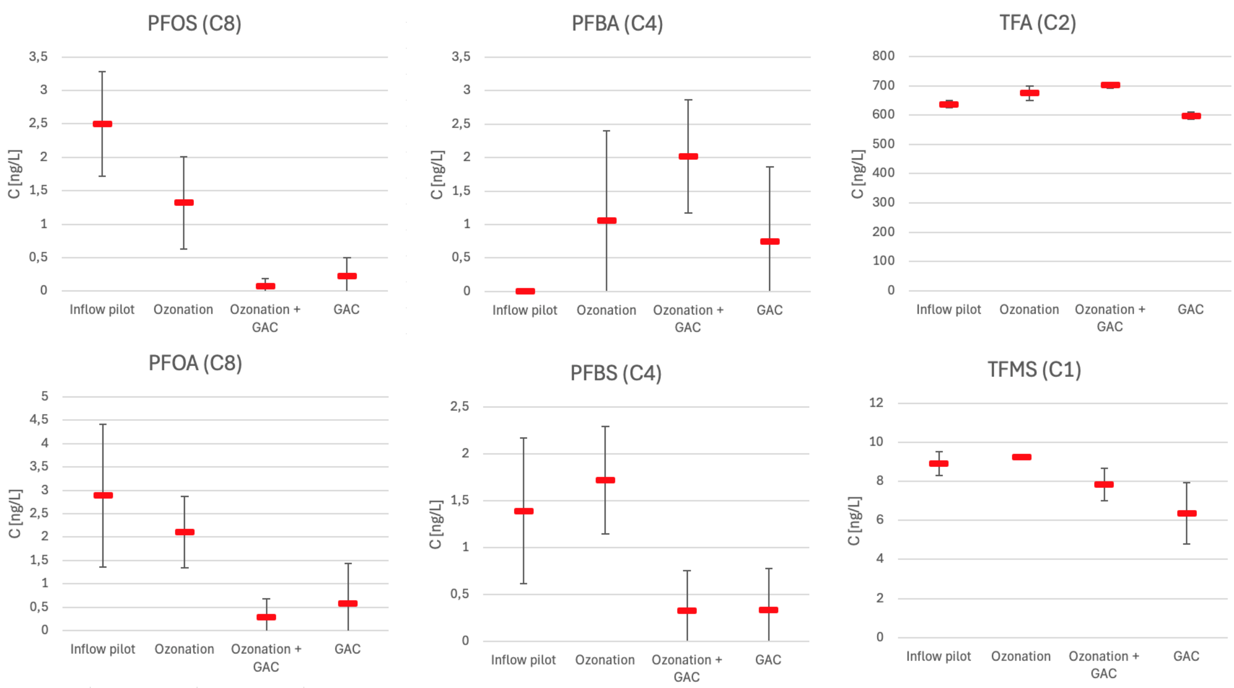

Figure 8. Concentrations of PFOS, PFOA, PFBA, PFBS, TFA and TFMS during the pilot plant operation in Turku (Annex VI).

The observed increase in short-chain PFAS during ozonation can be explained by the oxidative breakdown of longer-chain PFAS molecules into smaller fragments (Figure 8). While ozone is capable of partially degrading persistent long-chain PFAS, the process does not result in full mineralization. Instead, shorter-chain transformation products are formed, which are more mobile, less sorptive, and more difficult to remove by conventional adsorption processes.

In contrast to ozonation, GAC treatment showed somewhat more stable removal performance across all analyzed PFAS. Nevertheless, the same general trend was observed: larger PFAS molecules were removed with higher efficiency than smaller ones. For very short-chain compounds such as C1 and C2 PFAS (e.g., TFA and TFMS), only a minor degree of removal was achieved, and the effect remained very limited.

In summary, the pilot trials demonstrated that neither ozonation nor GAC alone can be regarded as an effective stand-alone strategy for PFAS removal. Ozonation may even shift the PFAS profile towards more mobile short-chain compounds, while GAC provides only limited retention of these smaller molecules. Both results highlight the need for complementary treatment technologies—such as anion exchange or nanofiltration—where PFAS removal is a priority.

4.4. Ozonation technology

In addition to its application in quaternary treatment, ozonation technology has long been widely used in both industrial wastewater treatment and drinking water purification. The German Water Association (DWA) has also issued a technical standard DWA-M 285-3 [13], which specifies the recommended contact time for ozonation (>20 minutes). At the same time, the technology continues to evolve, with developers seeking solutions to improve the cost-efficiency of the process.

Accordingly, two different ozonation configurations were applied in the pilot plants of this project. In Pilot Plant A, conventional ozone dosing was implemented by introducing gas into the wastewater through fine-bubble diffusers installed at the bottom of the contact tank. At the Gdańsk, Szczecin, and Kaunas WWTPs, typical contact times of 15 to 40 minutes were used in line with standard practice. In Pilot Plant B, however, ozone was injected directly into the feed pipe based on supplier recommendations, resulting in locally higher ozone concentrations. This allowed the system to operate with significantly shorter contact times in the contact tank, typically 3 to 5 minutes.

Although the project did not include a dedicated comparative evaluation of these two ozonation approaches, both configurations proved to be effective. No significant differences were observed in overall ozonation performance; the main variations were related to the applied ozone dosages. Lower removal efficiencies for metoprolol and candesartan were observed in both pilot plants. It should be emphasized, however, that when planning full-scale investments, the influence of contact time and the method of ozone introduction on pollutant removal efficiency must be carefully considered.

4.5. Combination of Ozonation and GAC technologies

As discussed in the previous sections, both ozonation and GAC treatment were found to be effective in removing a broad range of OMPs. The general conclusion from the pilot trials conducted at different treatment plants was that, in most cases, the 80% removal requirement of the UWWTD was met. However, when the focus is extended to include PFAS, it is clear that ozonation alone does not significantly reduce their concentration.

Literature also supports the sequential combination of ozonation followed by activated carbon filtration as a promising strategy. This approach achieves a synergistic effect: ozone reduces the load of OMPs and improves the biodegradability of by-products, while GAC absorbs residual compounds and ozone transformation products. At the same time, pre-ozonation reduces the burden on the GAC filters, thereby prolonging their service life and improving overall cost-efficiency. Such benefits of ozonation–GAC combinations have been documented in full-scale applications in Switzerland, Germany, and Sweden [3].

In the present study, ozonation followed by GAC filtration was tested at several sites. At some plants, longer-term trials were carried out using two parallel GAC filters, one treating ozonated effluent and the other operating without pre-ozonation. As already discussed, both technologies perform well on their own for OMPs removal. However, when operated in series, the combined effect consistently yielded the highest removal efficiencies. Although removal rates for PFAS were lower overall, the same trend was observed—ozonation followed by GAC provided the most stable performance.

Even though the pilot operating periods were relatively short, the results from the Turku WWTP provide an illustrative example. For the pharmaceutical candesartan, the GAC filter treating ozonated effluent ("GAC A") maintained nearly complete removal for a substantially longer period, whereas the parallel GAC filter without pre-ozonation ("GAC B") showed breakthrough after approximately one month of operation (Figure 9). This effect was most evident in cases where ozonation itself already had a strong effect on the compound.

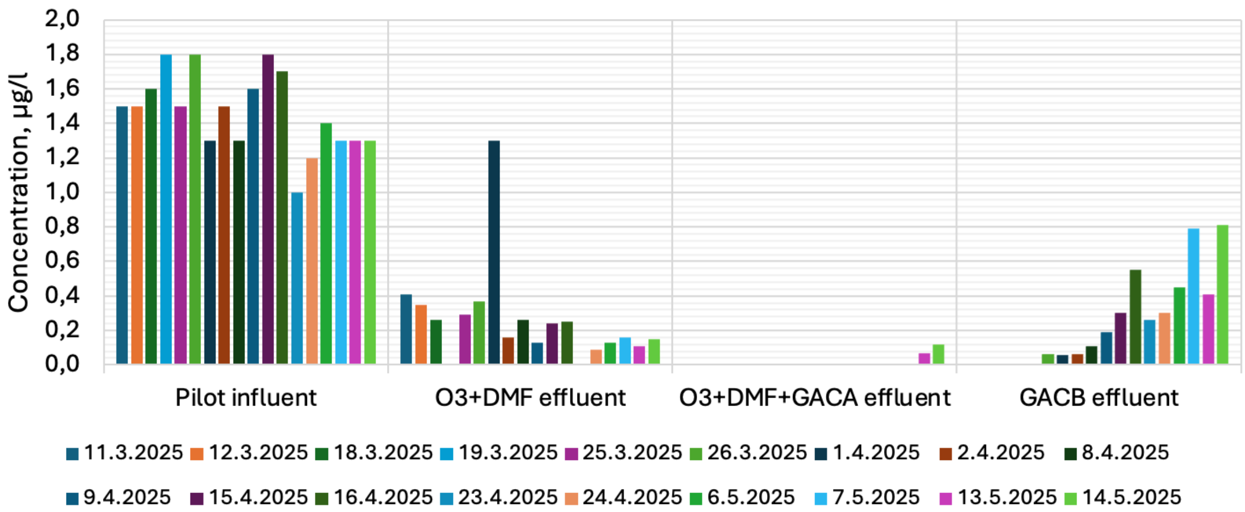

Figure 9. Removal of Candesartan during the pilot plant operation in Turku (Annex VI).

Due to the limited duration of the trials, it was not possible to provide a robust quantification of the cost-efficiency of the combined approach. Nevertheless, both the literature and the pilot results support the conclusion that ozonation followed by GAC is the most effective and robust configuration for quaternary treatment, offering both higher pollutant removal and improved sustainability of carbon filter operation.

4.6. Specialized PFAS removal technologies – ion exchange and nanofiltration

As shown in the preceding sections, both GAC and ozonation provide only limited effectiveness for PFAS removal. By contrast, nanofiltration (NF) and ion exchange (IX) have previously been demonstrated as highly effective technologies for PFAS elimination.

In Pilot Plant A, ion exchange was tested using the resin DuPont Amberlite™ PSR2 Plus. The IX process proved to be highly effective for PFAS removal, including those compounds that had shown poor removal performance under ozonation and GAC adsorption (Figure 10). For example, during the trials at the Gdańsk WWTP, no removal of perfluorohexanoic acid (PFHxA, C6) was achieved with ozonation or GAC. Furthermore, the concentration of PFHxA increased after ozonation due to partial oxidation of long chain PFAS. IX treatment removed this compound completely (see Annex I) (Figure 10). The trials conducted in Gdańsk achieved very strong removal of a wide range of OMPs using IX combined with ozonation and GAC filtration. IX is best regarded as a complementary or alternative process in cases where highly efficient PFAS removal is required.

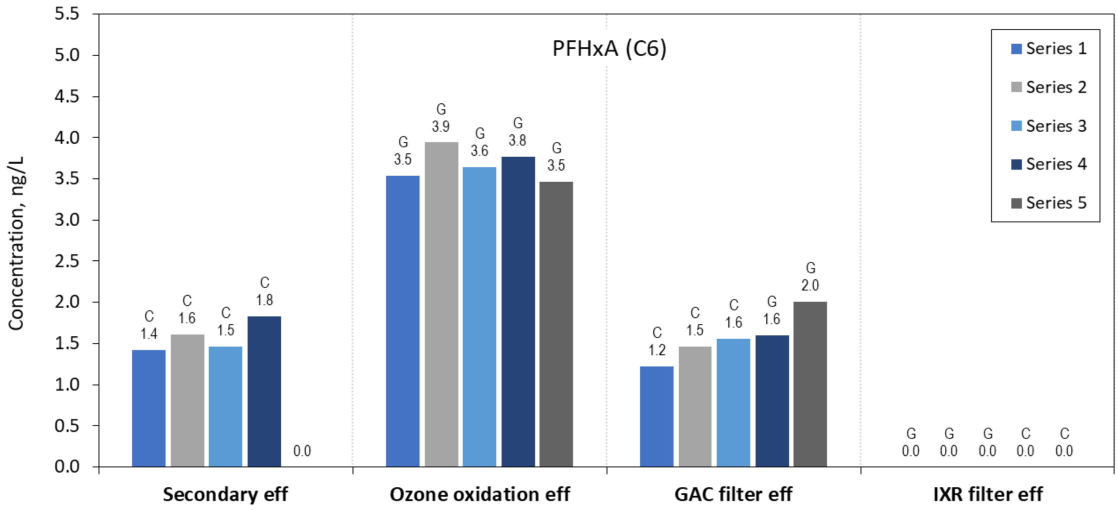

Figure 10. Removal of PFHxA (C6) by ozone, GAC and IXR filter during the pilot plant operation in Gdansk (Annex I).

In Pilot Plant B at the Tartu WWTP, additional trials were conducted with nanofiltration (NF) using the dNF40 membrane with cut-off 400 Dalton (see Annex IV). As expected, given the molecular size of PFAS, NF achieved very high removal rates for all investigated PFAS. The sum of PFAS24 expressed in PFOA equivalents was reduced by more than 99%. The performance of NF for OMPs, however, was more variable. For many compounds the removal was above 80% (e.g. diclofenac), but for certain persistent OMPs the removal efficiency was considerably lower.

Thus, nanofiltration can be considered a relevant option primarily in cases where PFAS removal is a significant treatment objective. However, a key limitation is the generation of a relatively large reject stream containing concentrated PFAS and OMPs, which requires secondary treatment or safe disposal.

Both ion exchange and nanofiltration demonstrated excellent effectiveness for PFAS removal in the pilot trials. Ion exchange resins achieved complete removal of problematic PFAS compounds such as PFHxA, while nanofiltration consistently reached >99% removal of the PFAS24 sum. Their performance for OMPs was less consistent, highlighting the need to integrate these technologies with other processes (e.g. ozonation and GAC). IX and NF therefore represent strong alternatives where PFAS elimination is a priority, but their implementation must also consider operational costs, resin/membrane management, and reject handling.

5. Conclusions

- The EMPEREST project successfully tested and demonstrated the efficiency of advanced treatment technologies for removing organic micropollutants (OMPs) listed as indicator substances in the revised Urban Wastewater Treatment Directive (UWWTD 2024/3019), using mobile pilot plants across six cities in the Baltic Sea region. The project results support wastewater treatment plant operators and experts in making informed decisions about cost-effective and scalable technologies tailored to local conditions and regulatory requirements.
- PFASs are not removed with high efficiency by conventional water treatment processes. Advanced treatment technologies such as activated carbon, ion exchange, and membrane filtration if applied individually can only partially remove PFASs, with short-chain compounds being particularly difficult to eliminate. One of the most effective technologies currently available for removing PFAS, especially long-chain compounds, is ion-exchange resins, which often form part of a larger treatment system. PFASs analysis remains complex and costly, which limits routine monitoring and assessment.
- Including advanced oxidation processes in the treatment system, such as ozonation, can transform long-chain PFAS into shorter-chain PFAS, leading to an apparent increase in their concentrations in treated wastewater. Therefore, broad analytical screening is essential to accurately assess PFAS removal, especially when using advanced oxidation processes.
- Mobile pilot containers enabled flexible testing of ozonation, granular activated carbon (GAC) filtration, ion exchange, and nanofiltration, generating comparative performance data under real-world conditions.
- The findings contribute to evidence-based planning for large-scale investments required by the revised Urban Wastewater Treatment Directive (UWWTD).
- EMPEREST facilitated knowledge transfer and capacity building among regional stakeholders, promoting cooperation in technology development, pilot testing, and operational readiness.
- Systematic sampling and chemical analysis at each pilot site provided valuable insights into the removal efficiency of pharmaceuticals, PFAS, and other micropollutants, supporting future implementation strategies.

6. References

[1] M. Tarigan, S. Raji, H. Al-Fatesh, P. Czermak, and M. Ebrahimi, “The Occurrence of Micropollutants in the Aquatic Environment and Technologies for Their Removal,” *Processes*, vol. 13, no. 3. 2025, doi: 10.3390/pr13030843.

[2] Markus Raudkivi, “Methodological recommendations for the monitoring and assessment of PFAS in the aquatic environment,” *HELCOM*, 2025, [Online]. Available: https://interreg-baltic.eu/project/emperest/#output-0.

[3] A. Pistocchi *et al.*, “Treatment of micropollutants in wastewater: Balancing effectiveness, costs and implications,” *Sci. Total Environ.*, vol. 850, p. 157593, 2022, doi: https://doi.org/10.1016/j.scitotenv.2022.157593.

[4] J. Jurík, B. Jankovičová, R. Zakhar, N. Šoltýsová, and J. Derco, “Quaternary Treatment of Urban Wastewater for Its Reuse,” *Processes*, vol. 12, no. 9. 2024, doi: 10.3390/pr12091905.

[5] T. W. Ltd, “Roadmap for advanced effluent treatment pilot investments,” 2023, [Online]. Available: https://interreg-baltic.eu/project/emperest/.

[6] G. W. U. Ltd, “Roadmap for advanced effluent treatment pilot investments,” 2023, [Online]. Available: https://interreg-baltic.eu/project/emperest/.

[7] European Parliament and Council, *Water Framework Directive 2000/70/EC*. 2000.

[8] E. P. and of the Council, “Urban Wastewater Treatment Directive,” *Official Journal of the European Union*, 2024. https://eur-lex.europa.eu/eli/dir/2024/3019/oj/eng.

[9] J. Ianes, S. Piraldi, B. Cantoni, and M. Antonelli, “Micropollutants removal, residual risk, and costs for quaternary treatments in the framework of the Urban Wastewater Treatment Directive,” *Water Res. X*, vol. 29, p. 100334, 2025, doi: https://doi.org/10.1016/j.wroa.2025.100334.

[10] M. Bourgin *et al.*, “Evaluation of a full-scale wastewater treatment plant upgraded with ozonation and biological post-treatments: Abatement of micropollutants, formation of transformation products and oxidation by-products,” *Water Res.*, vol. 129, pp. 486–498, 2018, doi: https://doi.org/10.1016/j.watres.2017.10.036.

[11] F. A. Zeidabadi, E. B. Esfahani, S. T. McBeath, and M. Mohseni, “Managing PFAS exhausted Ion-exchange resins through effective regeneration/electrochemical process,” *Water Res.*, vol. 255, p. 121529, 2024, doi: https://doi.org/10.1016/j.watres.2024.121529.

[12] C. Baresel *et al.*, “Handbok för rening av mikroföroreningar vid avloppsreningsverk - Planering och installation av reningstekniker för läkemedelsrester och andra mikroföroreningar,” *IVL Sven. Miljöinstitutets Slutrapporter*, no. B2288, pp. 1–112, 2017, [Online]. Available: http://sjostad.ivl.se/download/18.1369484715f59ce4bab17f/1509705944359/Slutrapport B2288 - Handbok för rening av mikroföroreningar vid avloppsreningsverk.pdf.

[13] ATV-DVWK, “DWA-M 285 Spurenstoffentfernung auf kommunalen Kläranlagen - Teil 3: Ozonung - Verfahrensgrundsätze und Bemessung.” Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., p. 44, 2024.